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A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF PLANAR PIN THERMOPHOTOVOLTAIC CELLS

FINAL REPORT

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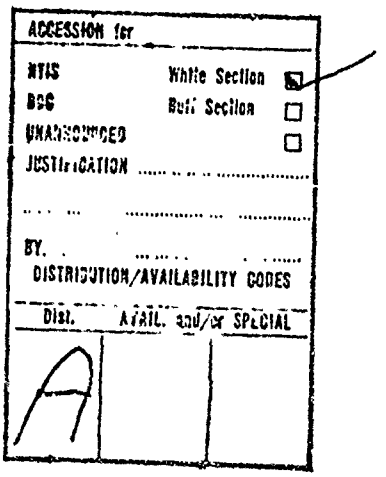

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Experimental work leading to the fabrication of interdigitated p-i-n thermophotovoltaic cells is described. The results of tests evaluating the performance of fabricated cells are discussed. A series of experiments were carried out to determine why the performance of these cells was below theoretical expectations.

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A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF PLANAR PIN THERMOPHOTOVOLTAIC CELLS

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The results of calculations of the performance of a planar p-i-n thermophotovoltaic cell are reported. A computer program has been written which automatically optimizes the cell geometry. The program allows the bulk recombination rate, the surface recombination velocity, the hole and electron mobilities and the intensity and spectrum of radiation illuminating the cell to be chosen arbitrarily. The performance of germanium p-i-n cells is investigated for monochromatic radiation and radiation from 1873°K erbium oxide and black body sources.

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SYMBOL LIST*

ℓ_n = width of n contact

ℓ_p = width of p contact

ℓ_i = spacing between contacts

x_o = thickness of device

n = excess carrier concentration

e = electron charge

n_i = intrinsic carrier concentration

V = voltage

k = Boltzmann's constant

T = temperature in ^oK

*All symbols used in the FORTRAN program are defined in Tables XII and XIII.

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INTRODUCTION

This is a final report on the work which was performed under contract number DAAB07-70-C-0129. This report contains a detailed description of the work performed from June 1, 1971 to June 1, 1972 under the above contract. Previous work covering the period from June 1, 1970 to June 1, 1971 which was performed under the same contract has been reported in the annual report TR ECOM-0129-1. This report, which will be referred to as Report No. 1,[1] was published in August, 1971 with the control symbol OSD-1366.

The purposes of this contract were to theoretically investigate germanium p-i-n planar photovoltaic cells, to determine the optimum design of such cells for thermophotovoltaic use and to fabricate germanium p-i-n cells which represent the present state of the art. Figure 1 shows a cross section view and a view from the contact side of a planar p-i-n structure.

One of the purposes of this investigation is to determine if the p-i-n structure has a significant advantage over the standard p-n photovoltaic cell in thermophotovoltaic applications. In order to do this, the performance of the p-i-n cell had to be analyzed under a variety of operating conditions. This was done with a computer program which would allow the computation of cell performance under a variety of specified incident radiation spectra as well as a variety of materials parameters such as surface recombination velocity, bulk recombination rate and mobility. The computer program was described in Report No. 1.[1] During the last year of the contract this program has been expanded to allow for automatic optimization of the device dimensions when the incident radiation spectrum,

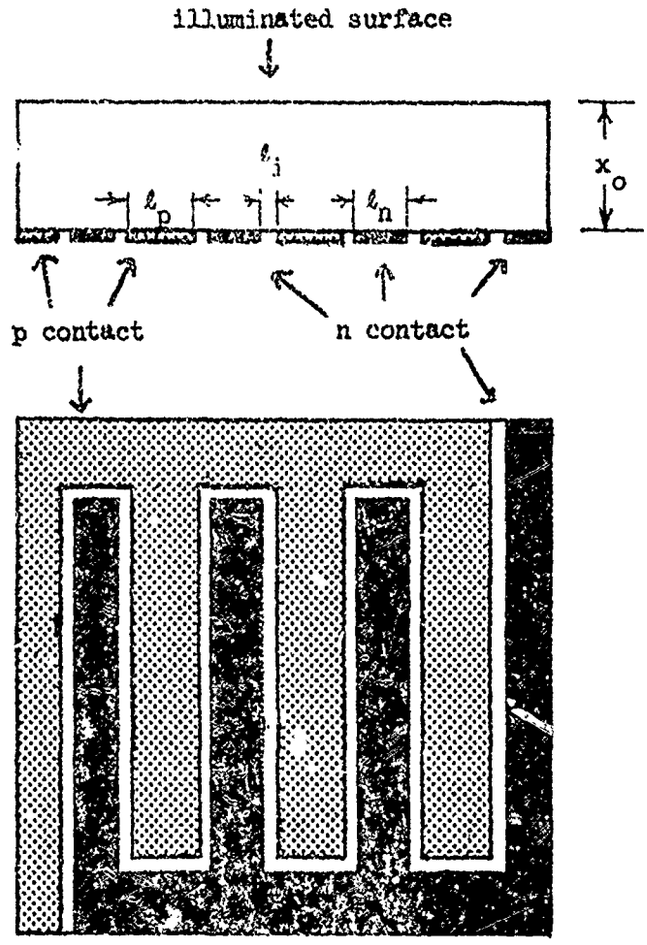


Figure 1. Planar p-i-n Thermophotovoltaic Cell

surface recombination velocity and the bulk recombination rate are specified. The first part of this report deals with the results of this optimization program.

Three distinct types of radiation spectra were selected for study - monochromatic radiation, black body radiation at 1873°K and radiation from an erbium oxide radiator at 1873°K. The analysis with monochromatic radiation is of little practical value, but it provides insight into the performance of the cell with other radiation spectra. The analysis with the erbium oxide radiator is of interest, because the spectral emissivity of erbium oxide is relatively large for photons with energies near the direct gap in germanium and relatively small for photons with energies well above or well below the direct gap energy. Thus, radiation from an erbium oxide source can be converted into electrical energy more efficiently than radiation from a black body source.

The second part of this report deals with the experimental program. It contains a description of the procedure used to fabricate p-i-n photovoltaic cells and of the investigations that were carried out in connection with the fabrication process. The results which have been obtained to date on the performance of germanium p-i-n photovoltaic cells are discussed. A series of tests was carried out to determine why the performance of these cells is below theoretical expectations.

In the third part of the report the most significant theoretical and experimental results are briefly discussed and recommendations are made for future work.

I. THEORETICAL INVESTIGATIONS

A. Introduction

In Report No. 1[1] the results of the program to optimize the design for a device illunimated by black body radiation were described. It was clear from these results that additional optimization calculations needed to be performed to determine the effects of various spectra as well as the effects of changes in surface recombination velocity and bulk recombination rate on the performance of the device. A new program was written which utilized essentially the same approach for evaluating the performance of the device as the program described in Report No. 1[1] but which also automatically optimized the dimensions of the device. This Automatic Device Optimization Program (ADOP) is described in the appendix.

B. Lifetime Considerations

In Report No. 1 we pointed out that in the usual operating range for a p-i-n photovoltaic cell, the lifetime of the excess carriers will be determined primarly by radiative recombination rather than by recombination through trap sites. In Figure 2 we show a curve of the excess carrier concentration as a function of minority carrier lifetime for which the rate of recombination due to recombination through trap sites is equal to the rate of recombination due to radiative recombination. The curve is also plotted in terms of open circuit voltage which can be correlated directly to excess carrier concentration. If the open circuit voltage for a particular minority carrier lifetime lies above the curve, the dominant recombination mechanism will be radiative

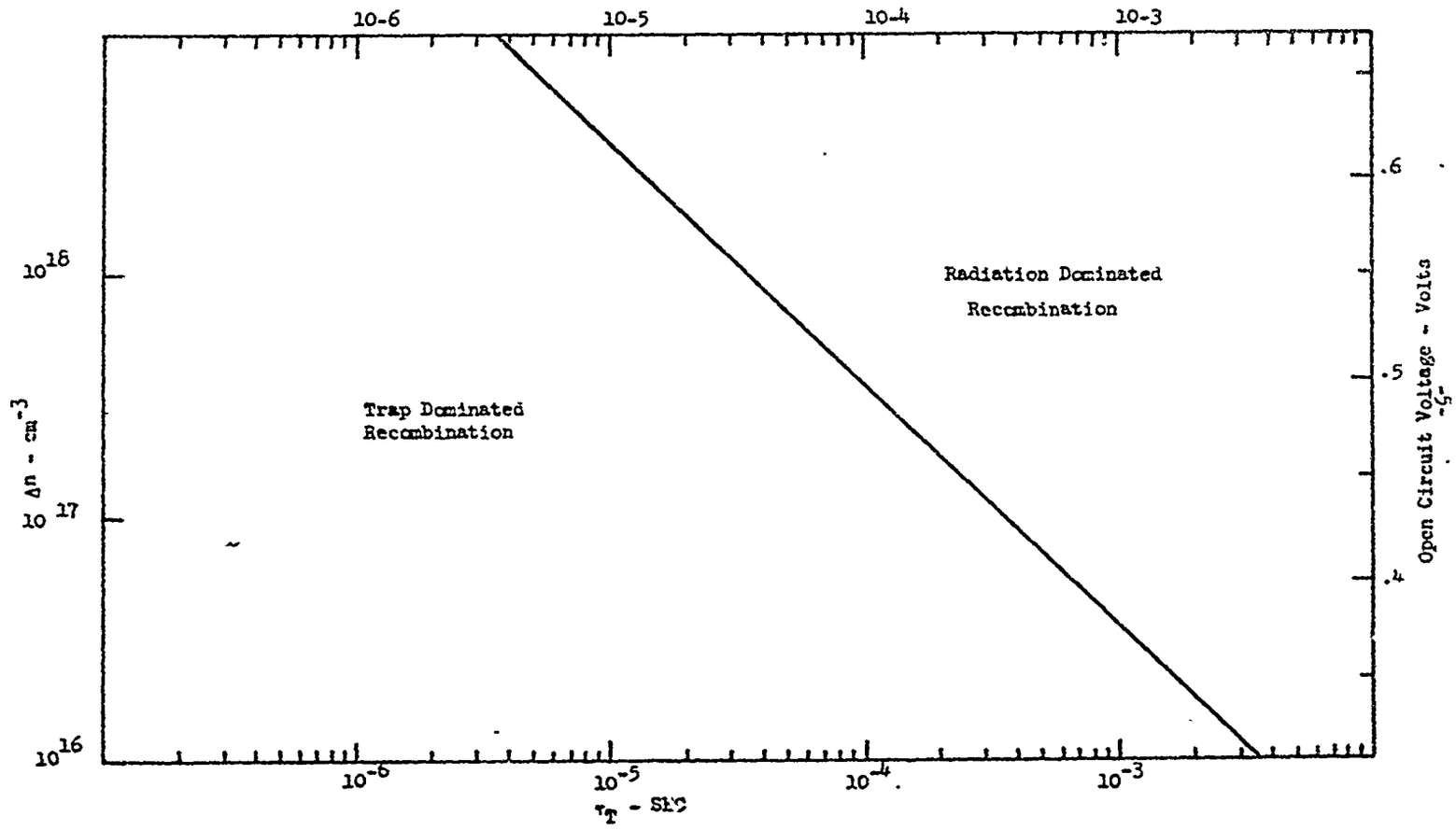


Figure 2. Excess Carrier Concentration and Open Circuit Voltage at Which Bulk Radiative Recombination Equals Bulk Trap Recombination

recombination. If the open circuit voltage lies below the curve, the dominant recombination mechanism will be recombination through trap sites. Since the minority carrier lifetime for the starting material is in excess of 2×10^{-3} seconds, it appears that for operating conditions which would normally be found in the operation of a photovoltaic cell, (ΔN 10^{17} electrons cm^{-3}) the dominant recombination mechanism would be radiative recombination. If, however, the minority carrier lifetime in the bulk is significantly reduced during processing (say to a value of 10 to 100 μ sec.), then the dominant recombination mechanism would not be radiative recombination, and one should base lifetime calculations on the usual Hall-Shockley-Reed type recombination statistics. Since the purpose of using intrinsic material is to obtain a very high minority carrier lifetime in the bulk, we have assumed for all of our calculations that the dominant recombination mechanism is radiative recombination. The radiative recombination parameter is found to be equal to 2.8×10^{-10} cm^3 sec^{-1} from fundamental thermodynamic arguments.[6] None of the devices, which are described in chapter II, were operated in the radiation recombination region during performance tests, performed under this contract. The reasons for this are discussed in chapters II and III.

c. Results

The results obtained from the ADOI program are summarized in Tables I, IV, V and VI. The results for monochromatic radiation will be analyzed in considerable detail. Many of the conclusions drawn from these results will be applicable to those obtained for black body radiation and radiation from an erbium oxide source.

1. Monochromatic radiation

The performance of the n-i-n cell has been analyzed for three different wavelengths of monochromatic radiation. The wavelengths were chosen so that their absorption lengths would vary over a range of values which would be

approximately equal to realistic values of device thickness (x_o). The three wavelengths chosen were 1.50 μm, 1.54 μm and 1.60 μm with respective absorption lengths of 2.3 μm, 21 μm and 104 μm. An absorbtion length is defined as the distance into the germanium at which 63% of the incident radiation has been absorbed.

The results of the output obtained from the ADOP program for monochromatic radiation are summarized in Table I, and Figure 3. The spacing between contacts (LI) is fixed at 25 μm. The maximum current collectable per unit area of illuminated surface, if every photon capable of generating a hole-electron is absorbed (CHRDOPT), is fixed at 5 amps/cm^2. The following observations can be made from the results in Table I:

1) When the excess carrier concentration is very large, the optimum device thickness is determined primarily by two conflicting factors. The device should be as thick as possible in order to absorb as much of the incident radiation as possible. On the other hand, as the device gets thicker the volume in which recombination can take place increases, while the relative increase in the number of photons absorbed tends to become smaller. Therefore the excess carrier concentration must decrease. This, of course, results in a reduction of output voltage.

The dependence of open circuit voltage and short circuit current on device thickness is shown in Table II. The data in this Table is obtained from the output of the program from which device 11 was optimized. Note that as XO increases, the open circuit voltage and maximum power point voltages decrease, while the short circuit current and maximum power point current increase.

In cases where VSB and VST are both 0 (devices #1, 11 and 20), the optimum thickness (XO) is roughly four absorption lengths. About 90% of the incident photons are absorbed in four absorption lengths.

TABLE I

Optimum Dimensions and Output Parameters of Devices Illuminated with Monchromatic Radiation*

LI = 25 μm CURDOPT = 5.0 amp cm^{-2} RCOMPAC = 2.8 x 10^{-4} cm^{3} sec.$^{-1}$

	Device #	VSB (cm sec^{-1})	VST (cm sec^{-1})	LN (μm)	LP (μm)	XO (μm)	PMAXPOW (watt cm^{-2})	ETACELL (%)	ETACOL	ETAABS	CF	VOC (volts)	CURDSC (amp cm^{-2})
Absorption Wavelength = 1.50 μm Length = 2.1 μm	1	0	0	12.18	20.29	10.98	2.224	67.80	1.000	.9938	.8150	.5491	4.969
	2	0	0	30.62	50.96	50+	2.049	62.10	1.000	1.000	.8036	.5100	5.000
	3	10	10	118.7	200.9	50+	1.963	59.47	.999	1.000	.7772	.5056	4.99
	4	100	100	130.8	224.4	50+	1.594	48.29	.9893	1.000	.6854	.4701	4.946
	5	1000	1000	89.26	146.1	50+	.9551	28.94	.9036	1.000	.5861	.3607	4.518
	6	0	10	30.67	51.14	50+	1.976	59.89	.9991	1.000	.7317	.5061	4.995
	7	0	100	30.76	51.74	50+	1.634	49.50	.9909	1.000	.6958	.4739	4.954
	8	0	1000	31.34	55.25	50+	1.027	31.13	.9164	1.000	.6073	.3692	4.582
	9	10	0	131.9	224.7	50+	2.034	61.65	.9999	1.000	.7986	.5095	5.000
	10	100	0	332.5	523.0	50+	1.986	60.17	Unreliable	1.000	.7463	.5078	Unreliable
Absorption Wavelength = 1.54 μm Length = 21 μm	11	0	0	56.25	83.57	91.83	1.942	59.65	.9999	.9864	.7971	.4939	4.932
	12	10	10	123.0	203.7	99.33	1.879	57.45	.9986	.9910	.7769	.4888	4.948
	13	100	100	169.0	282.3	114.5	1.570	47.79	.9940	.9954	.6950	.4612	4.987
	14	1000	1000	136.4	210.4	94.83	.9569	29.29	.8837	.9900	.6012	.3638	4.375
	15	0	10	56.19	83.72	98.47	1.888	57.76	.9986	.9906	.7801	.4894	4.946
	16	0	100	56.27	84.36	111.6	1.601	48.72	.9849	.9958	.7039	.4639	4.904
	17	0	1000	56.82	87.58	84.85	.9959	30.64	.9027	.9848	.6056	.3700	4.445
	18	10	0	132.3	219.2	93.05	1.931	59.28	.9999	.9872	.7934	.4932	4.936
	19	100	0	321.1	522.0	97.43	1.896	58.03	Unreliable	.9900	.7793	.4909	4.956

(Continued on next page)

(Table I continued)

Absorption Length = 1/α	Device #	VSB (cm sec^{-1})	VST (cm sec^{-1})	LN (μm)	LP (μm)	XO (μm)	PMAXPOW (watt cm^{-2})	ETACELL (%)	ETACOL	ETAABS	CF	VOC (volts)	CURDSC (amp cm^{-2})
Wavelength = 1.60 μm	20	0	0	128.1	197.2	376.0	1.694	52.81	.9969	.9722	.7658	.4565	4.846
	21	10	10	154.6	236.9	381.7	1.661	51.69	.9922	.9738	.7563	.4546	4.831
	22	100	100	215.7	350.4	390.6	1.437	44.59	.9534	.9762	.7004	.4407	4.654
	23	1000	1000	216.1	360.5	297.0	.7865	25.30	.7754	.9420	.5868	.3670	3.652
	24	0	10	119.7	187.0	380.8	1.664	51.80	.9923	.9736	.7575	.4584	4.830
	25	0	100	126.6	197.0	383.7	1.452	45.01	.9533	.9756	.7064	.4420	4.651
	26	0	1000	146.0	226.6	297.7	.8139	26.17	.7742	.9424	.6000	.3718	3.648
	27	10	0	156.3	238.9	377.2	1.691	52.69	.9968	.9724	.7646	.4563	4.847
	28	100	0	276.8	460.9	380.9	1.672	52.06	.9964	.9736	.7574	.4533	4.850

*The FORTRAN variables given in this table are defined on pages in Table XIV The estimated error in values of PMAXPOW is 1% or less. The values in the Table are listed as they appeared in the computer program printout. Although the output values are generally inaccurate beyond the second decimal place, small differences between two corresponding output values for different values of input parameters will generally be accurate to the third or fourth decimal place.

+Devices #1 through #10 are optimized under the constraint that the minimum attainable device thickness is 50 μm, because of limitations in fabrication technology.

TABLE II

Dependence of Output Parameters on Device Thickness*

$\lambda = 1.54\ \mu m$

LN = 50 μm LP = 75 μm $V_{SB} = V_{ST} = 0$

XO (μm)	VOC (volts)	CURDSC (amp cm^{-2})	VMAXPOW (volts)	CMAXPOW (amp cm^{-2})	PMAXPOW (watt cm^{-2})
25.0	.5186	3.475	.4441	3.274	1.454
37.5	.5127	4.158	.4385	3.913	1.716
50.0	.5075	4.535	.4334	4.263	1.848
62.5	.5029	4.743	.4289	4.455	1.911
75.0	.4988	4.858	.4249	4.558	1.937
87.5	.4951	4.921	.4213	4.614	1.944
100	.4918	4.956	.4181	4.642	1.941
125	.4861	4.986	.4124	4.661	1.922
150	.4814	4.995	.4077	4.661	1.900
175	.4773	4.997	.4035	4.656	1.879
200	.4738	4.996	.3999	4.648	1.859

*The FORTRAN variables given in this table are defined in Table XIV The data is obtained from the output of the program from which device 11 of Table I was optimized.

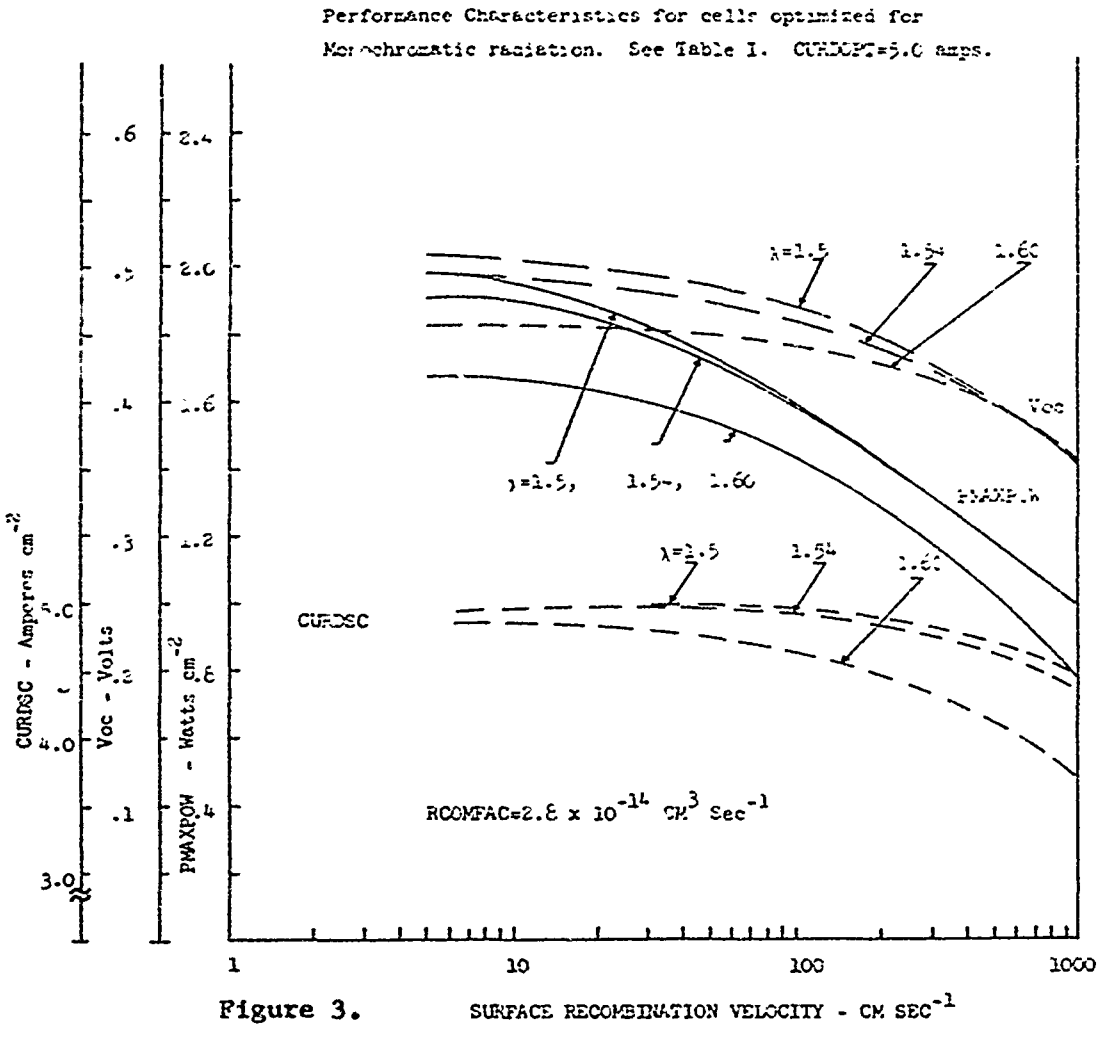

Performance Characteristics for cells optimized for
Monochromatic radiation. See Table I. CURDOPT=5.0 amps.
CURSC - Amperes cm-2
Voc - Volts
PMAXPOW - Watts cm-2
.6
.5
.4
.3
.1
5.0
4.0
3.0
2.4
2.0
1.6
1.2
.8
.4
λ=1.5
1.54
1.60
Voc
λ=1.5, 1.54, 1.60
PMAXP.h
λ=1.5
1.54
1.60
CURDSC
RCOMFAC=2.8 x 10-14 CM3 Sec-1
1
10
100
1000
SURFACE RECOMBINATION VELOCITY - CM SEC-1

Figure 3.

2) In cases where VST and VSB are both 0 (device #1, 11 and 20), PMAXPOW increases as the absorption length decreases. This is because the optimum value of XO is smaller and therefore the volume in which excess carriers are generated is smaller. Hence, the number of carriers generated per unit volume is greater, and the open circuit voltage developed at the contacts is greater. This conclusion can be collaborated by a comparison of open circuit voltages for devices 1, 11 and 20. Note that the relative variation in open circuit voltage is much greater than the relative variation in short circuit current.

A second advantage resulting from larger excess carrier concentrations is a reduction in the resistivity of the bulk and, therefore, a reduction in ohmic loss due to the flow of current between contacts. However, this effect is almost negligible for the large excess carrier concentrations in devices 1, 11 and 20.

3) It would appear that the optimum contact widths LN and LP exhibit a strong dependence on the surface recombination velocity. For instance, in the case of devices 2 and 3, a small increase in the values of VSB and VST from 0 to 10 cm sec^{-1} causes the optimum value of LN to change from 31 μm to 119 μm and the optimum value of LP to change from 51 μm to 201 μm. These changes, however, are not significant; for even though the optimum contact sizes change greatly, the output power is quite independent of contact sizes for small values of surface recombination velocity. This is shown for devices 2 and 3 in Table III. These devices are illuminated with radiation of a 1.50 μ wavelength. The output power shows similar lack of dependence on LN and LP for samples illuminated with radiation of other wavelengths when surface recombination velocities are small.

TABLE III

Variation in Maximum Power Output for Different Contact Widths

(Devices 2 and 3 from Table I)

$X0 = 50\ \mu m$

VBS ($cm\ sec^{-1}$)	VST ($cm\ sec^{-1}$)	LN (μm)	LP (μm)	PMAXPOW ($watt\ cm^{-2}$)
0	0	30.6*	51.0*	2.049
		5	100	2.048
		25	100	2.048
		12.5	50	2.048
		25	37.5	2.049
10	10	118.7*	200.9*	1.963
		150	250	1.962
		50	250	1.960
		50	200	1.961
		150	150	1.962

*Optimized dimensions.

4) As VSB increases while VST is held constant at 0 (devices 9, 10, 18, 19, 27 and 28), there is a tendency for LN and LP to increase. The effect of increasing LN and LP while holding LI constant is to decrease the fraction of the unilluminated surface which is subject to surface recombination. Thus, fewer excess carriers are lost due to recombination on the unilluminated surface. This tendency for the contact size to increase is counterbalanced by an increase in the series resistance in the device as the average distance between the center of the p contact and the center of the n contact is increased. Thus, as the recombination velocity on the rear surface increases from a value of zero to a larger value, we observe LN and LP increasing until the series resistance begins to dominate.

5) In cases where VST is increases while VSB is held at 0 (devices 15-17 and 24-26) there is a tendency for the device thickness to increase slightly until VST exceeds 100 cm/sec. The tendency for the optimum device thickness to increase can be accounted for by realizing that as the surface recombination velocity increases the relative importance of bulk recombination velocity decreases. As XO increases, the average excess carrier densit decreases. This in turn, decreases the total recombination. Increasing XO also increases the number of carriers generated, although the effect is quite small when XO is greater than three absorption lengths. As the excess carrier concentration decreases, VOC decreases. Thus, the optimum value of XO represents the best compromise between these competing needs. The optimum value of XO will change as the relative importance of the surface recombination changes.

When the surface recombination velocity exceeds 100 cm sec^{-1}, the optimum thickness tends to decrease. This is because the excess carrier concentration becomes low enough to invalidate the assumption that the

excess carrier distribution is fairly uniform in the bulk region. Since most of the excess carriers are generated within one absorption length of the illuminated surface and since these carriers must diffuse to the contacts to be collected, the excess carrier concentration in the region of the contacts tends to be significantly less than the average excess carrier concentration in the bulk region when there is an appreciable current flowing through the contacts. Thus the maximum power point voltage will tend to be significantly reduced. The device tends to become thinner to minimize the reduction of excess carrier concentration in the region of the contacts due to the diffusion gradient.

6) In cases where VST and VSB are held equal (devices 2-5, 11-14 and 20-23), the effects of surface recombination occuring on the illuminated surface only and on the unilluminated surface only are combined. Thus, IN and LP increase as VSB increases to 100 cm $sec.^{-1}$, and (for devices 11-14 and 20-23) XO increases as VST increases to 100, but starts to decrease as VST increases to 1000.

2. Radiation from an erbium oxide source

The results obtained from the ADOP program for devices illuminated with radiation from an 1873°K erbium oxide source are summarized in Tables IV and V. The current-voltage curves of these devices are plotted Figures 4 and 6. In general the observations made for devices illuminated with monochromatic radiation are applicable to these devices.

For an idealized device (device 29) the conversion efficiency is 14.7%. If VST is held at 0, very little degradation of output power occurs for values of VSB smaller than 100 cm $sec.^{-1}$ On the other hand, if VSB is held at 0, there is a significant degradation in the output power

TABLE IV

Optimum Dimensions and Output Parameters of Devices Illuminated with 1873°K Erbium Oxide Spectrum*

LI = 25 μm RCOMFAC = 2.8 x 10^{14} cm^3/sec

	Device #	VSB ($cm\ sec^{-1}$)	VST ($cm\ sec^{-1}$)	LN (μm)	LP (μm)	XO (μm)	PMAXOW ($watt\ cm^{-2}$)	ETACELL (%)	ETACOL	ETAABS	CF	VOC (volts)	CURDSC ($amp\ cm^{-2}$)
Incident Power = 9.2 watt cm^{-2}	29	0	0	128.5	196.8	401.2	1.350	51.79	.9966	.7894	.7634	.4493	3.936
	30	10	10	155.6	239.3	417.8	1.320	50.42	.9903	.7936	.7525	.4466	3.929
	31	100	100	218.6	356.8	437.0	1.122	42.62	.9387	.7976	.6946	.4314	3.743
	32	500	500	207.1	341.5	266.6	.7466	30.03	.8425	.7534	.6125	.3841	3.174
CURDOPT = 5 amp cm^{-2}	33	1000	1000	147.0	244.5	159.2	.5731	24.58	.8092	.7066	.5794	.3460	2.859
	34	0	10	121.1	179.5	414.2	1.324	50.59	.9905	.7928	.7542	.4470	3.926
	35	0	100	126.2	196.2	433.2	1.134	43.13	.9388	.7968	.7007	.4328	3.740
	36	0	1000	108.9	162.0	160.7	0.5989	25.65	.8128	.7074	.5910	.3524	
	37	10	0	157.9	243.0	404.4	1.347	51.64	.9964	.7906	.7618	.4489	3.939
	38	100	0	293.9	485.8	414.1	1.33	50.92	.9959	.7928	.7540	.4476	3.947
Incident Power = 16.4 watt cm^{-2}	39	0	0	120.5	179.4	344.4	2.793	54.47	.9957	.7768	.7672	.4706	7.735
	40	10	10	151.1	228.7	353.7	2.742	53.35	.9904	.7786	.7584	.4688	7.711
	41	100	100	202.4	324.5	374.4	2.401	46.42	.9453	.7837	.7102	.4564	7.409
CURDOPT = 10 amp cm^2	42	500	500	187.3	311.5	248.1	1.676	34.00	.8505	.7471	.6329	.4169	6.354
	43	1000	1000	152.5	252.8	159.6	1.311	28.10	.8116	.7069	.5986	.3817	5.737
Incident Power = 1.84 watt cm^{-2}	44	0	0	164.2	254.9	518.7	.2457	45.82	.9984	.8174	.7537	.4018	.8111
	45	10	0	225.7	355.8	580.1	.2358	43.51	.9898	.8212	.7323	.3962	.8128
	46	100	100	314.9	512.0	607.6	.1619	33.40	.9200	.8251	.6476	.3704	.7590
CURDOPT = 1 amp cm^{-2}	47	500	500	219.4	363.7	287.4	.1078	21.48	.8303	.7605	.5613	.3040	.6318
	48	1000	1000	159.6	264.1	169.9	.07839	16.67	.7929	.7125	.5254	.2641	.5649

*The FORTRAN variables given in this table are defined in Table XIV The estimated error in values of PMAXPOW is 1% or less. The values in the Table are listed as they appeared in the computer program printout. Although the output values are generally inaccurate beyond the second decimal place, small differences between two corresponding output values for different values of input parameters will generally be accurate to the third or fourth decimal place

Current Voltage Curves of Devices Illuminated with Erbium Oxide Spectra.
(Devices are labeled according to device numbers in Table IV.)

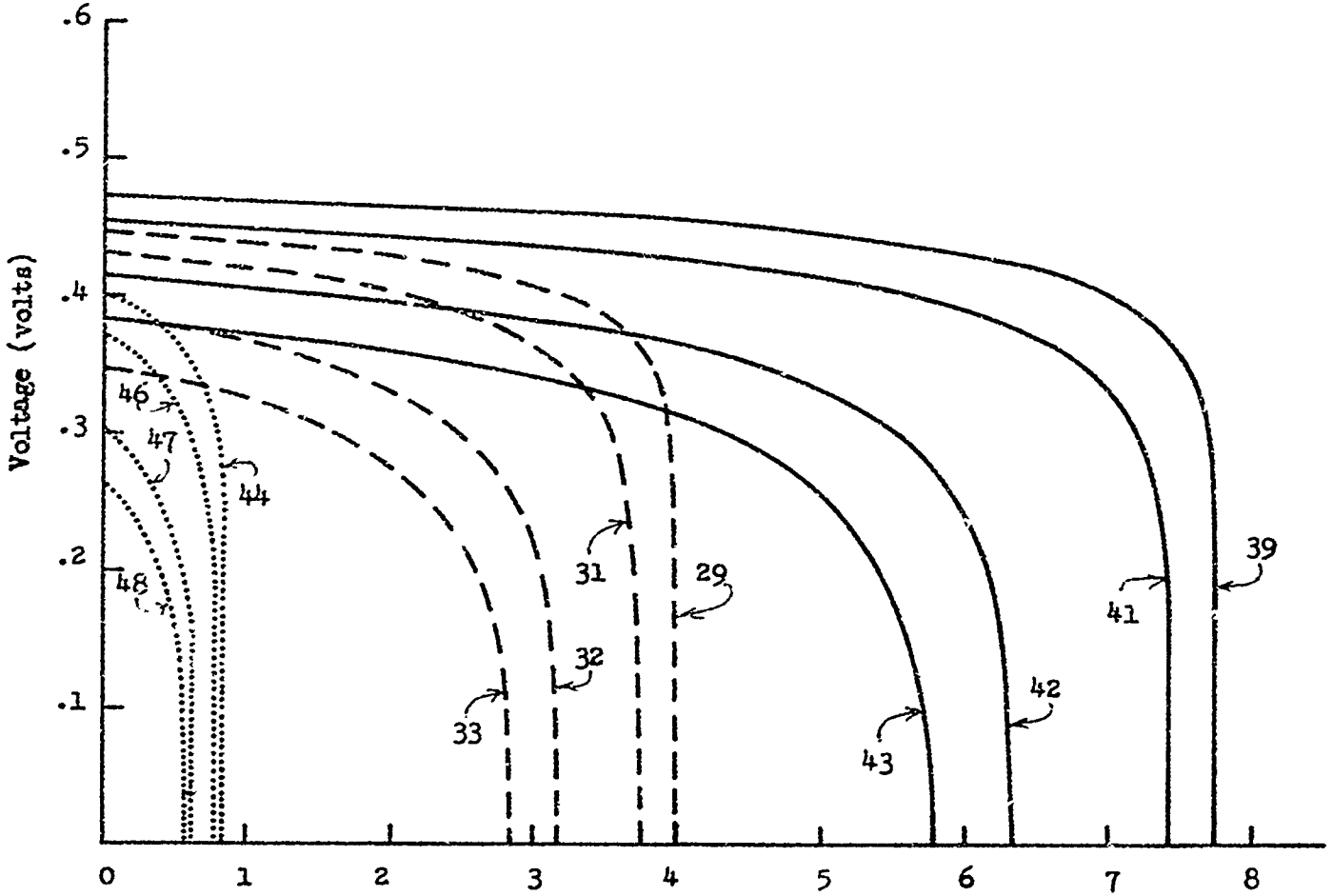


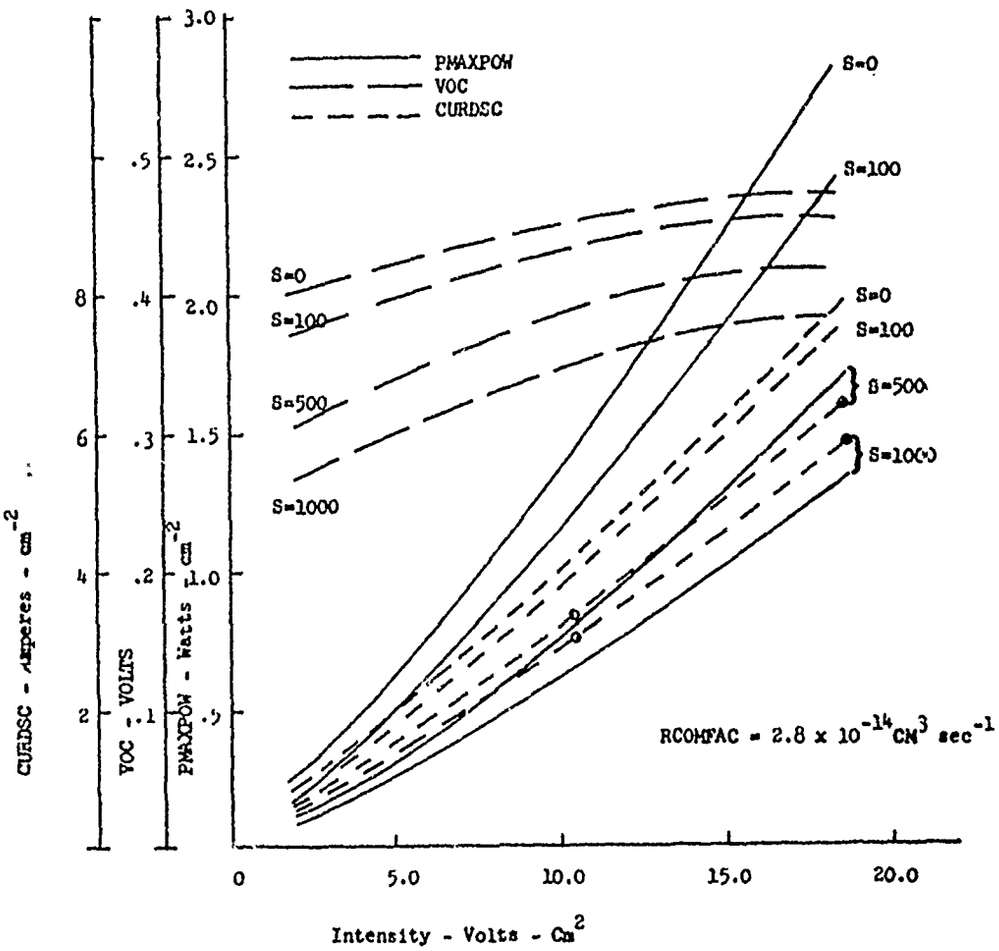
Figure 4.

as VST is increased from 0 to 100 cm sec^{-1}. This is because the area of the illuminated surface is much greater than the area of the portion of the unilluminated surface between contacts.

For devices where the surface recombination velocity is the same on both the illuminated an unilluminates surfaces, the majority of the surface recombinations occur on the illuminated surface. However, it is expected that during processing it will be more difficult to maintain low surface recombination velocity on the unilluminated surface. Therefore, the total number of recombinations on either surface should be of comparable magnitude.

Some of the results of Table IV have been plotted in Figure 5. As would be expected the output power increases faster than a linear rate with increasing incident radiation intensity. However, because the radiativ recombination increases as the square of the excess carrier concentration, the rate of rise in output power with increasing intensity is not as rapid as would be the case if all recombination occurred through trap sites.

The effect of recombination through trap sites is shown by the results summarized in Table V These results are plotted in Figure 6. It is interesting to note that the open circuit voltages of devices 49 and 50 are greater than the open circuit voltage of device 29. This is because the recombination rate tends to vary linearly with the excess carrier concentration (n/τ) rather than with the square of the excess carrier concentration (rn^2). Therefore, as the device becomes thinner, the relative increase in excess carrier concentration and open circuit voltage will be greater.



Performance characteristics of cells optimized for radiation from an Er_2O_3 radiator. VSB=VST. See Table IV for device dimensions.

FIGURE 5

TABLE V

Optimum Dimensions and Output

Parameters of Devices with Finite Bulk Lifetimes*

VSB = VST = 0 LI = 25μM RCOMFAC = 2.8×10^{-4} cm^3 sec^{-1}

Incident Power = 9.2 watt cm^{-2} CURDOPT = 5amp. cm^{-2}

Device #	TAU (μ - sec)	LN (μM)	LP (μM)	XO (μM)	PMAXPOW (watt-cm^{-2})	ETACELL (%)	CF	VOC (volts)	CURDSC (amp-cm^{-2})
29	∞	128.5	196.8	401.2	1.350	51.79	.7634	.4493	3.936
49	1000	116.0	169.3	289.3	1.272	50.66	.7461	.4517	3.774
50	100	54.95	81.71	78.70	1.024	48.08	.6973	.4578	3.207
51	10	31.03	53.48	50+	.6975	34.74	.6210	.3778	2.966

*The FORTRAN variables given in this Table are defined in Table XIV. The devices are illuminated with on 1873°K Erbium Oxide Spectrum. The estimated error in [etc. (same as in Table IV.)

+Device 51 is optimized under the constraint that the minimum attainable device thinkness is 50μM because of limitations in fabrication technology.

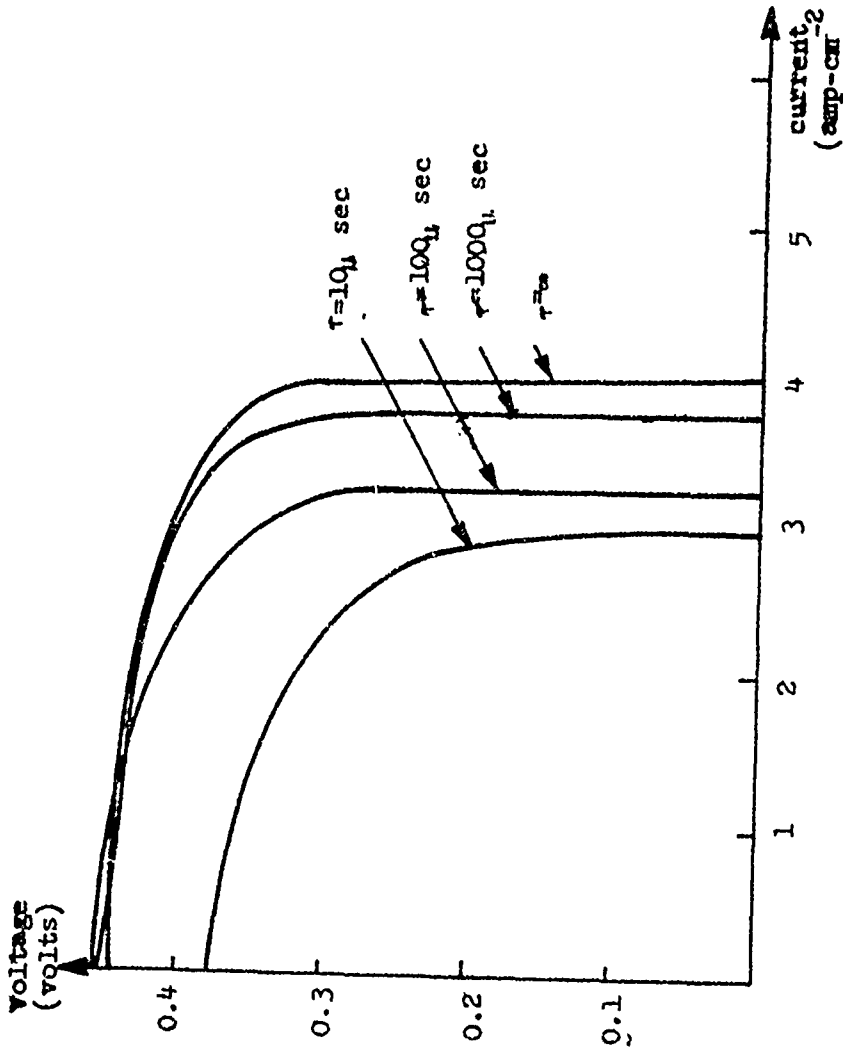


Figure 6. Current Voltage Curves of Devices with Finite Bulk Lifetimes

Consequently, the optimum thickness will tend to be smaller and the open circuit voltage will tend to be greater.

3. Radiation from a black body source

The results obtained from the ADOP program for devices illuminated with radiation from an 1873°K black body are summarized in Table VI. In general, for the same value of CURDMAX, the optimum device dimensions occured at slightly larger values for black body radiation than for erbium oxide radiation. The conversion efficiency is also lower because a larger portion of the radiation energy is in unfavorable portions of the energy spectrum. Device 52 (Table VI) has a conversion efficiency of 12.7% when illuminated with 1873°K blackbody radiation while device 29 (Table IV) has c conversion efficiency of 14.7% when illuminated with 1873% Er_2O_3 radiation. In both cases the value of CURDOPT is 5.0 amps cm^{-2}.

TABLE VI

Optimum Dimensions and Output Parameters of Devices

Illuminated with 1873°K Black Body Spectrum*

LI = 25 μm Incident Power = 9.8 Watt cm $^{-2}$ CURDOPT = 5.0 amps cm^{-2}

RCOMFAC = 2.8×10^{-14} cm^3 sec^{-1}

Device #	VSB (cm sec^{-1})	VST (cm sec^{-1})	LN (μm)	LP (μm)	XO (μm)	PMAXPOW (watt cm^{-2})	ETACELL (%)	ETACOL	ETAABS	CF	VOC (volts)	CURDSC (amp cm^{-2})
52	0	0	150.3	224.3	508.5	1.241	50.07	.9935	.7508	.7532	.4416	3.730
53	10	10	170.1	264.7	520.2	1.214	48.85	.9861	.7532	.7439	.4395	3.714
54	100	100	234.1	377.8	530.8	1.029	41.30	.9258	.7552	.6912	.4259	3.496
55	500	500	221.2	366.6	321.1	.6705	28.81	.8184	.7052	.6104	.3807	2.886
56	1000	1000	157.9	262.7	179.5	.5070	23.65	.7927	.6496	.5760	.3420	2.573
57	0	10	152.5	229.3	518.0	1.216	48.96	.9861	.7528	.7451	.4398	3.762
58	0	100	154.3	234.2	526.0	1.040	41.77	.9262	.7544	.6968	.4272	3.493
59	0	1000	166.8	265.3	375.0	.0540	21.20	.6717	.7204	.5875	.3545	2.420
60	10	0	179.1	286.2	510.9	1.239	49.96	.9936	.7514	.7518	.4414	3.733
61	100	0	291.3	477.5	519.9	1.226	49.33	.9928	.7532	.7450	.4402	3.739

*The FORTRAN variables given in this table are defined in Table XIV The estimated error in values of PMAXPOW is 1% or less. The values in the Table are listed as they appeared in the computer program printout. Although the output values are generally inaccurate beyond the second decimal place, small difference between two corresponding output values for different values of input parameters will generally be accurate to the third or fourth decimal place.

II. EXPERIMENTAL INVESTIGATIONS

A. Introduction

The discussion of the experimental work will consist of the following: (1) a brief description of the device fabrication process; (2) a detailed description of investigations involving the fabrication process; (3) a discussion of the performance of devices that have been fabricated, and (4) a listing of the deficiencies which exist in devices that have been fabricated and a description of tests that have been carried out to isolate these deficiencies and measure their effects.

B. Description of Device Fabrication Process

The steps involved in fabricating a TPV cell are given below.

1. An intrinsic germanium wafer is chemically polished on both sides.[2]

2. An insulating film is deposited on both sides of the wafer.

3. A pattern for the formation of the n contact is etched in the insulator on one side of the wafer.

4. Metal(s) for the n contact is vacuum evaoprated on the wafer.

5. The metal(s) is etched so that it covers only the portion of the wafer on which the insulator has been etched. (See Figure 7.)

6. A pattern for the formation of the p contact is etched in the insulator.

7. Metal(s) for the p contact is vacuum evaporated on the wafer.

8. The metal(s) is etched so that it covers only that portion of the wafer on which the insulator has been etched for the p contact.

9. The contact metals are alloyed to the germanium. (See Figure 8.)

During the course of the experimental work some devices were fabricated according to the above procedure. A number of variations in this procedure were investigated, and a variety of insulating films and contact metals were investigated.

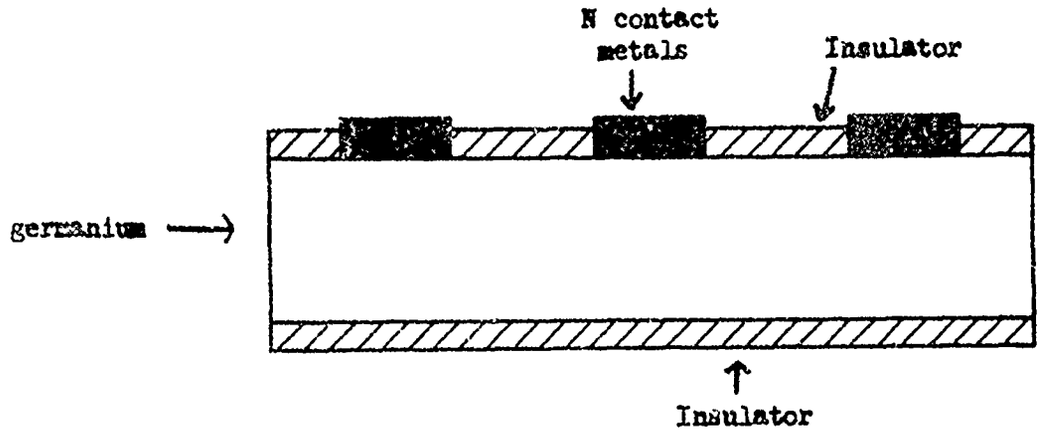


Figure 7. Partially Fabricated p-i-n Thermophotovoltaic Cell

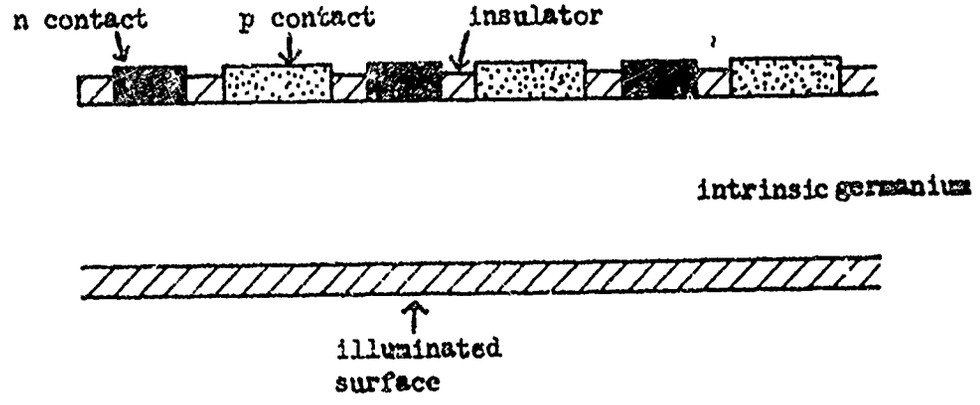


Figure 8. Completely Fabricated p-i-n Thermophotovoltaic Cell

C. Experimental Investigations of the Fabrication Process

1. Insulator deposition

The insulators which have been investigated are pyrolytically deposited silicon dioxide and vacuum deposited aluminum oxide.

Silicon dioxide deposition.-- It is desirable to carry out device processing at the lowest possible temperature in order to prevent diffusion of lifetime destroying impurities into the germanium bulk. Therefore, an investigation was carried out in order to determine the lowest possible temperature at which the silicon dioxide could be deposited. A reasonably fast deposition (900 Å/min) could be obtained at a temperature as low as 310°C.

A method of device fabrication was proposed in Report No. 1[1] in which the p contact was formed before the n contact. Aluminum was to be used for the p contact. After the aluminum was deposited, etched and alloyed, silicon dioxide was deposited on top of the aluminum. Windows for n contacts were then etched in the silicon dioxide, and metals (gold and antimony) for the n contact were subsequently evaporated and alloyed. The necessity of etching the n contact metals was to be eliminated because of the insulating layer between the aluminum and the n contact metals.

The results of attempts to fabricate devices with the above described procedure were as follows: In cases where the silicon dioxide layer was deposited on top of the aluminum contact at 360°C, the p and n contacts were invariably shorted. Furthermore, the silicon dioxide invariably cracked on the aluminum once the thickness of the silicon dioxide exceeded 2000 Å. Devices for which the silicon dioxide was deposited at 425°C were occasionally workable.

Aluminum oxide deposition.-- An investigation was carried out to determine if vacuum evaporated aluminum oxide could be used as an insulating layer between contacts. It was observed, however, that, while aluminum oxide appeared to cover the top of the aluminum contact well, it did not cover the contact edges.

Photoresist problems with SiO_2 films.-- The positive photoresist AZ-1350* is generally used during the device fabrication. When this photoresist is used on pyrolytically deposited silicon dioxide, it is necessary to take certain precautions.

First of all, the developer which is normally used with this photoresist (AZ-1350 Developer*) contains an abundance of sodium ions. Since silicon dioxide is highly permeable to sodium ions, and since it is feared that these ions will have a detrimental effect on the surface recombination velocity, it is desirable to use the developer XP-7110-1.*

Secondly, AZ-1350 has a tendency not to stick to pyrolytically deposited silicon dioxide, and, therefore, it is necessary to take extra precautions to insure adhesion.

2. Contact formation

In order to avoid excessive leakage of minority carriers through the contacts, it is necessary that the contacts be very heavily doped and fairly thick. The requirement of low temperature processing rules out the use of high temperature diffusion techniques because of the danger of diffusion of lifetime destroying impurities into the germanium bulk. Heavily doped contacts can be obtained with alloying techniques, but in order to obtain sufficiently thick regrowth regions, it is necessary either to alloy at high temperatures or to deposite rather thick films

*Mfg. by Shipley.

of contact metals (1μm or thicker). Experimental investigations have shown that the thickness of vacuum deposited films is limited because of the effects of surface tension in the films. The increased surface tension of thick films has two adverse effects: (1) There is a tendency for the films to ball up or develop craters during the alloying process. (2) The adhesion of the films is poorer.

n contacts

Kim[4] has investigated several combinations of metals for forming alloyed n contacts and has found that the best results were obtained when gold was used as a carrier with arsenic and antimony being used as dopants. For this reason investigations were carried out in which these metals were to be used to form alloyed n contacts. It was discovered that vacuum deposited films of gold and antimony adhered very poorly to germanium, and, therefore, it was impossible to etch these films without removing them from the germanium. Because of this adhesion problem, several attempts were made to build a device without having to etch the gold-antimony film. The first of these attempts is described on page .

The second attempt was identical to the first attempt except that the deposition of silicon dioxide on the aluminum contact pattern was ommitted. Instead, a second layer of aluminum was evaporated and etched to cover the first layer of aluminum. After the gold-antimony film was evaporated, it was alloyed to the germanium at a temperature below the aluminum-germanium eutectic . It was hoped that the unalloyed aluminum film would not be affected by the gold-antimony layer on it during the alloying process. Then the alloyed gold-antimony film (which would stick to the germanium during the photo etching process) could be etched to separate the n contact

from the p contact. It was evident, however, that the gold-antimony film had interacted with aluminum film during the alloying process.

The proposed steps in the third attempt to fabricate a device were as follows: (1) Silicon dioxide would be deposited on both sides of a germanium wafer. (2) A pattern would be etched in the silicon dioxide on one side of the wafer through which the n contact would be formed. (3) Gold and antimony would be evaporated and alloyed to form the n contact. (4) The gold-antimony film would be etched so that it would remain only in those regions of the device on which the n contact pattern had been etched through the silicon dioxide. (5) A p contact pattern would be etched. (6) An aluminum film would be deposited and etched so that it would cover only the p contact region. (7) The aluminum would be alloyed to the germanium.

After the gold-antimony film had been alloyed [step (3)], however, large areas of balled-up gold-antimony alloy formed on the silicon dioxide. When step (4) was carried out, it was observed that the photoresist broke down before the thick balled-up regions could be completely etched.

An unsuccessful attempt was made to improve adhesion of gold to germanium by evaporating a mixture of gold and germanium simultaneously on a germanium wafer.

Eventually it was discovered that gold would adhere extremely well to germanium if the gold were evaporated immediately after the germanium surface had been subjected to an argon ion etch.*

*The ion etch is carried out at an argon pressure ranging from 50 microns to 10 microns while the vacuum system is pumping down the pressure. The duration of the ion etch is about 30 sec. The germanium wafer is in good electrical contact with a cathode that is maintained at a voltage of 600 volts D.C.

Several methods of "etching" the gold antimony films were investigated. These methods are described below:

Chemical etching.-- While chemical etching is procedurally complicated, it invariably produces sharp etches and can be used with relatively thick vacuum deposited films.

Ultrasonic "etching".-- Although gold sticks very well to ion etched germanium, it does not stick at all to silicon dioxide. Therefore step 5 of the procedure outlined in section B (page 24) can be carried out by removing the gold-antimony film from the silicon dioxide with a rigorous ultrasonic cleaning. Although this method of "etching" is procedurally simple, it has two disadvantages: (1) It does not produce as sharp a pattern as chemical etching. (2) It tends to become less satisfactory as the gold-antimony film becomes thicker. This is because the adhesion of the film to germanium becomes poorer.

Photoresist lift-off "etching".-- A third method of "etching" can be carried out as follows: (1) A photoresist pattern is developed on the wafer. (2) The metal film is deposited. (3) The photoresist and the metal film on top of it are stripped from the wafer, leaving a metal pattern which complements the photoresist pattern.

This method of etching has three disadvantages: (1) It does not produce as sharp a pattern as chemical etching. (2) It does not work for films that are too thick. (The photoresist won't lift off thick films.) (3) It is inherently dirtier than chemical or ultrasonic etching.

The advantage of photoresist lift-off etching is that the problem of etching the second metal contact pattern without attacking the first is eliminated.

A device was built using lift-off etching techniques. The processing steps were as follows: (1) Silicon dioxide was deposited on both sides of a wafer. (2) Both p and n contact patterns were etched in the wafer. (3) A photoresist pattern was developed which left only the p contact region uncovered. (4) An aluminum film was deposited. (5) The photoresist and the aluminum film above it were stripped from the wafer. (6) A photoresist pattern was developed which left only the n contact region uncovered. (7) Gold and antimony were deposited after an ion etch. (8) The photoresist and the gold-antimony film above it were stripped from the wafer.

Arsenic doped contacts.-- Investigations were carried out in which arsenic was used with gold or gold and antimony to form alloyed n contacts. Two noteworthy observations were made: (1) Arsenic-gold and arsenic-antimony-gold film tended to stick fairly well to germanium, provided that the arsemic was evaporated first. However, the films did not stick as well as gold antimony films of comparable thickness which had been deposited after an argon ion etch. (2) Alloyed arsenic-gold films tended to ball up much more readily than arsenic-antimony-gold films of comparable thickness.

Other combinations of metals have been investigated for n contacts. These investigations are discussed later.

p contacts

Aluminum has been thoroughly investigated as material fo. forming p contacts because of its very high solid solid solubility in germanium.

Thick films of aluminum (of the order of 10 μm) have been investigated because of the need to form thick germanium regrowth regions during

the alloying process. Because of the long time required to etch these films, the photoresist would break down, and pin holes would develop in the aluminum film. Experiments were conducted with various etchants and etching techniques to eliminate this problem. It was determined that photoresists would hold up satisfactorily if the film was etched in warm aluminum etch* (approximately 40°C).

Experiments have been conducted to determine if the adherence of aluminum films could be improved by an ion etch, (although aluminum films generally stick well without ion etches). The results indicate that the adherence of aluminum is improved slightly by an ion etch.

Other metals and combinations of metals have been investigated as materials for forming p contacts. The results of these investigations as well as the results of more detailed investigations of aluminum will be discussed in the following section.

Alloying

An extensive series of investigations was carried out in which various metal films and combinations of metal films were tested for possible use as p or n contacts. The metallic films were alloyed to the germanium at various temperatures and were angle-lapped and stained. The quality of the films was judged on the basis of the smoothness of the crystal regrowth region in the germanium.

Junction staining solution.-- Some preliminary tests were carried out in order to select a suitable junction staining solution. Aluminum balls were alloyed to germanium substrates to form thick heavily doped regrowth regions in the germanium. The substrates were lapped through the alloyed region and stained with various solutions. The best results were

*The composition of aluminum etch is given in Table VIII.

obtained with a 30 second stain in a solution consisting of 20 parts HF to one part HNO_3.

Alloying technique.-- All metallic films were vacuum deposited on chemically polished germanium substrates which had been cleaned ultrasonically in methanol, acetone and trichlorethylene and exposed to an argon ion etch.

The alloying was done in an alloying system in which the substrate was placed between two carbon heater strips. The heater strips could be heated independently, and thus the sample could be alloyed in a temperature gradient. The spacing between heater strips was about a half millimeter. The sample was placed on the lower heater strip with the surface on which the metallic film had been evaporated facing upward. The temperature of the upper strip was maintained about 100°C higher than that of the lower strip.* The alloying temperatures given in the following discussions are those of the lower substrates.

The samples were heated at a rate of about 10°C $sec.^{-1}$ A cooling rate of about 5° C sec^{-1} was begun immediately after the alloy temperature had been reached. All alloying was done in hydrogen.

Aluminum films.-- Aluminum films approximately one micron thick were deposited on germanium substrates. The films were alloyed at temperatures of 450°C, 500°C and 700°C. The samples were angle-lapped and stained. In the samples which were alloyed at 500°C and 700°C, the regrowth regions were extremely irregular, and there was no perceptable

*According to EerNisse[5] the regrowth region in the germanium substrate tends to be smoother when the temperature of the alloy melt is maintained above that of the germanium substrate.

regrowth in the sample which was alloyed at 450°C.

There was also a tendency for craters to form on the alloyed aluminum film. There was no perceptable regrowth in germanium regions under these craters.

Indium films.-- An indium film approximately one micron thick was deposited on a germanium substrate and alloyed at 650°C. The film balled up badly during the alloying process, and regrowth was visible only under the balled up regions.

Aluminum on indium films.-- Indium films (approximately one micron) followed by aluminum films (approximately one micron) were deposited on germanium substrates. The films were alloyed at 650°C, 500°C, 450°C and 350°C. The regrowth region of the film alloyed at 650°C was fairly smooth, but it got progressively more irregular for the films alloyed at 500°C and 450°. The regrowth region was quite smooth for the film alloyed at 350°C. This was probably due to the fact that the alloying temperature was below the germanium-aluminum eutectic (424°C), and, therefore, the aluminum film did not liquify during the alloying process.

The "cratering" effect described in the discussion of aluminum films also occured for these films. The craters tended to get progressively smaller at lower temperatures and were imperceptable for the film alloyed at 350°C.

Antimony on gold films.-- Gold films (approximately one micron) followed by antimony films (approximately one half micron) were evaporated on germanium substrates. The films were alloyed at 700°C and 525°C. The films balled up badly during the alloying processes, and regrowth was visible only under the balled up regions.

Antimony films.-- About three microns of antimony were evaporated on a germanium substrate and alloyed at a temperature of 700°C. The antimony balled up very badly during the alloying process, and no regrowth was visible in the germanium.

Tin-antimony-tin films.-- Some samples were prepared with a vacuum deposited film consisting of two layers of tin with a layer of antimony between them. The first and second layers of tin were approximately one half and one micron thick, and the antimony layer was approximately one half micron thick. The samples were alloyed at 475°C and 650°C. The regrowth regions were quite smooth and regular.

Conclusions.-- The most promising junctions for p contacts were obtained with the indium-aluminum films. The most promising junctions for n contacts were obtained with the tin-antimony-tin films. An attempt was made to fabricate a device using these films. It was discovered, however, that the adhesion of the films was not good enough.

An attempt was made to form tin-antimony-tin contacts on a device by alloying the film before etching it. Silicon dioxide was deposited on both sides of a wafer and was etched on one side to form an n contact pattern. A tin-antimony-tin film was evaporated and alloyed. But during the alloying process, the film balled up badly on the silicon dioxide, and apparently the surface tension created in the balled up regions on the silicon dioxide was large enough to cause the film to also ball up in the contact region.

Further investigations need to be carried out to determine the maximum thicknesses of indium-aluminum films and tin-antimony-tin films that will stick well enough to germanium to withstand ultrasonic cleaning and photoprocessing.

Contact buildup

Since the thermophotovoltaic cell is designed for very high intensity illumination, rather large currents will be collected at the contacts; and, consequently, it is necessary that the resistance in the contact fingers be quite low. Therefore, investigations were carried out in which the resistance of the contact fingers was reduced by plating relatively thick (10-20 micron) films of gold on the contacts.

Attempts were made to plate gold directly on the alloyed aluminum and gold-antimony contacts of a completed device. The gold plating on the aluminum did not stick at all. The gold plating on the gold-antimony contact appeared to stick reasonably well, but the plating on the gold-antimony fingers bridged over to the aluminum fingers in several places.

The following method of building up the contacts satisfactorily eliminated the bridging over problem and permitted a buildup of both aluminum and gold-antimony contacts: (1) Very thin chrome and gold films were evaporated over the contact surface of the device. (2) A relatively thick gold film was electroplated on the vacuum deposited gold film. (3) The chrome-gold film was then etched to separate the P and N contacts. The chrome film was evaporated to form an adhesive layer with the aluminum; and the gold film was evaporated subsequently without breaking vacuum in order to prevent oxidation of the chrome film and thus insure the adhesion of the electroplated gold film. It is desirable to build up the contacts with electroplated rather than evaporated gold, because thick films of evaporated gold would produce an appreciable amount of surface tension. This surface tension would cause stresses in the germanium which could significantly reduce lifetime.

3. Fabrication problems

Compatability of etchants and processing chemicals.-- A variety of chemicals and etchants are used in the process of fabricating a device. Some of the etchants which are quite satisfactory for etching the metal or insulator for which they are meant will attack other areas of the device. The fabrication process must be carried out in such a way that this doesn't happen. Table VII lists some of these chemicals and etchants and their effects on metals and insulators that are used in the fabrication process. The compositions of the etchants listed in Table VII are given in Table VIII.

Problems with gold contacting aluminum.-- The following process was used to fabricate the devices which were evaluated in the tests in section II-D: (1) Silicon dioxide was deposited on both sides of a wafer. (2) A pattern for n contacts was etched in the silicon dioxide. (3) A gold-antimony-gold* film was deposited and etched to form the n contact. (4) A pattern for p contacts was etched in the silicon dioxide. (5) An aluminum film was deposited and etched to form the p contact. (6) The contact metals were alloyed to the germanium.

A problem occured in step (5). Normally it is necessary to heat the device to a temperature of about 100°C for a period of about 30 minutes during the photoetching process. This heating period caused the aluminum to react with the gold. A method of photoprocessing without heating the device was developed in order to eliminate this effect.

*The film consisted of two layers of gold with a layer of antimony between them.

TABLE VII

Effect of Chemicals and Etchants on Metals and Insulators

Chemical & Etchants	Metals & Insulators: Germanium	Silicon Dioxide	Aluminum Oxide	Aluminum	Indium	Gold	Antimony	Arsenic	Tin	Chrome
Silicon Dioxide Etch	4	1		1						
Aluminum Etch	4	4	1	1	1	4	3			
Gold Etch	2	4		1A		1	4			
Antimony Etch	1	4		2	1	1	1	1	1	
Chrome Etch		4				4				1
Nitric Acid	4	4		2	1		2		1	
J-100	4	4	4	4		4	3			
Water		2A								

1. Etches rapidly.

1A. Does not attack aluminum but lifts of the aluminum by attacking the germanium surface under the aluminum film.

2. Etches slowly

2A. Causes flaking of film after several days immersion.

3. Has a discoloring effect.

4. Has no apparent effect.

TABLE VIII

Etchants used in Device Fabrication

Silicon Dioxide Etch:	104 ml	Hydrofluoric acid
	454 gm	Ammonium Fluoride
	682 ml	Water
Aluminum Etch:	380 ml	Phosphoric Acid
	15 ml	Nitric Acid
	75 ml	Acetic Acid
	25 ml	Water
Gold Etch:	27 gm	Iodine
	60 gm	Potasium Iodide
	600 ml	Water
Antimony Etch:	3 parts	Nitric Acid
	1 parts	Hydrochloric Acid
	6 parts	Water
Chrome Etch:	27 gm	Cerium Sulfate
	100 ml	Nitric Acid
	400 ml	Water

4. Heat sink fabrication and device mounting

A photograph of a finished device mounted on a heat sink is shown in Figure 9. The interior of the heat sink is hollow. Cooling water enters and exits through the openings at opposite ends of the heat sink. The portion of the heat sink under the device is milled to a thickness of 1/16 inch. The milled surface is left unfinished to facilitate the conduction of heat between the surface and the circulating water. The heat sink is anodized in sulfuric acid to form an insulating layer of aluminum oxide approximately 5 μm thick. The milled out portion is sealed at the bottom with an aluminum block which is epoxied on with stycast 2850FT*. Banana jacks are soldered on two copper contact plates which are epoxied on opposite sides of the heat sink with Stycast 2850FT*.

The device is epoxied to the heat sink with Stycast 2850FT* used with the catylist 24 LV. First of all, the device is mounted (the illuminated surface facing downward) on a glass slide with beeswax. The glass slide provides mechanical support. The device is than epoxied to the heat sink with the p and n contact pads extended over opposite edges of the heat sink. After the epoxy has cured the glass slide is removed by melting the beeswax, and the beeswax is removed with trichlorethylene. Finally the contacts on the device are soldered to the contact plates with Indalloy Solder #8 used with Flux #2.**

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*Manufactured by Emmerson Cumming.

**Manufactured by the Indium Corporation of America.

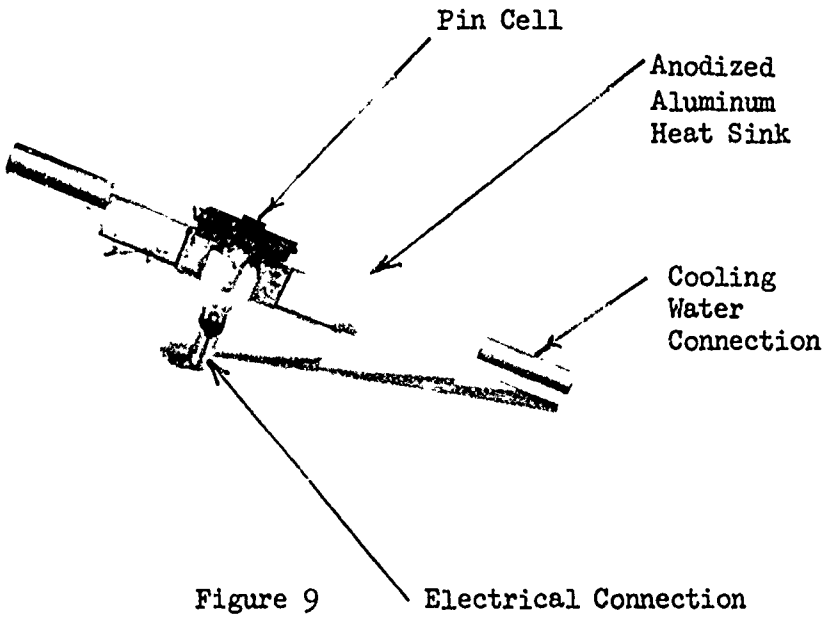

Figure 9 p-i-n Cell Mounted on Water Cooled Heat Sink

5. Evaluation of heat sink performance.

The following experiment was carried out to estimate the degradation in the performance of heat-sinked cells due to the heating effect of the 9.95 watt-cm^{-2} illumination source: A shutter was inserted between the cell and the illumination source to prevent heating of the cell. The I-V characteristics of the cell were monitored on a curve tracer. A series of traces on the curve tracer was photographed immediately after the shutter was removed. The effect of heating could be determined by observing the degradation in the I-V characteristics on the photograph of the traces.

In cases where there was no fluid circulating through the heat sink, a very significant degradation occured in the cell performance. In cases where there was water circulating through the heat sink, however, the degradation was practically imperceptable.

D. Performance of Fabricated Devices

Some devices were fabricated with the process outlined pages 24 and 25. The open circuit voltages of each device was measured in a sample holder in which the illuminated surface was faced downward on a glass slide. A tungsten lamp illuminated the sample through the glass slide with an incident intensity of 0.7 watts/cm^2. No measurements were made to determine what percentage of the incident light was absorbed by the sample.

The results of the open circuit voltage measurements are shown in Table IX. The Table also lists the unique characteristics of each device.

Two note worthy observations can be made from the data in Table IX: (1) The quality of the device generally improves as the film thickness (especially the thickness of the n-contact films) is increased. (2) The quality of devices alloyed at temperatures at or above 550°C is better than that of those alloyed below 550°C.

The open circuit voltage of device #4 was measured again with the 0.7 watt/cm^2 tungsten lamp being replaced with a 9.95 watt/cm^2 tungsten lamp. The measured open circuit voltage was 0.28 volts.

Devices #1, 4 and 6 in Table IX were mounted on heat sinks. Because of problems encountered with breakage during processing, the active area of device #1 was reduced to 0.6 cm x 0.55 cm. Problems were encountered with the adhesion of electroplated gold films on devices #1 and 4. As a result the performance of these devices was significantly degraded after they were mounted on the heat sinks.

The I-V characteristics of device #6 are shown in Figure 10. The 9.95 watt/cm^2 illumination source is used. The short circuit current

TABLE IX

Open Circuit Voltage Output of Fabricated Devices
0.7 w/cm^2 Tungsten Illumination

Device #	Active area (cm x cm)	Total Thickness of Gold Films (Å)	Thickness of Antimony Film (Å)	Thickness of Aluminum Film (Å)	Alloying Temperature (°C)	Open Circuit voltage (volts)
1*	0.6 x 1.5	300	300	1500	450	0.10
2	0.6 x 1.5	250	250	1500	450	0.06
3	0.55 x 0.30	1000	750	6000	450	0.12
4*	0.55 x 0.30	1000	750	6000	550	0.19
5	0.55 x 0.30	500	250	12000	550	0.165
6*	0.55 x 0.30	500	250	12000	550	0.16
7	0.5 x 0.30	500	250	6000	700	0.14

*Mounted on heat sinks

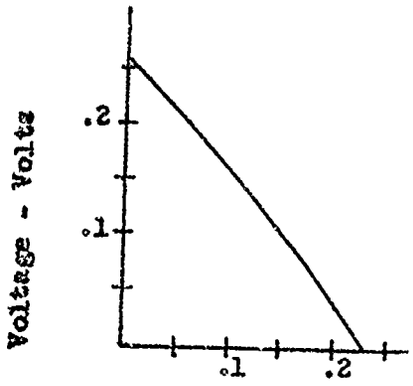

Figure 10. Voltage Curves for Device #6 (See Table IX)

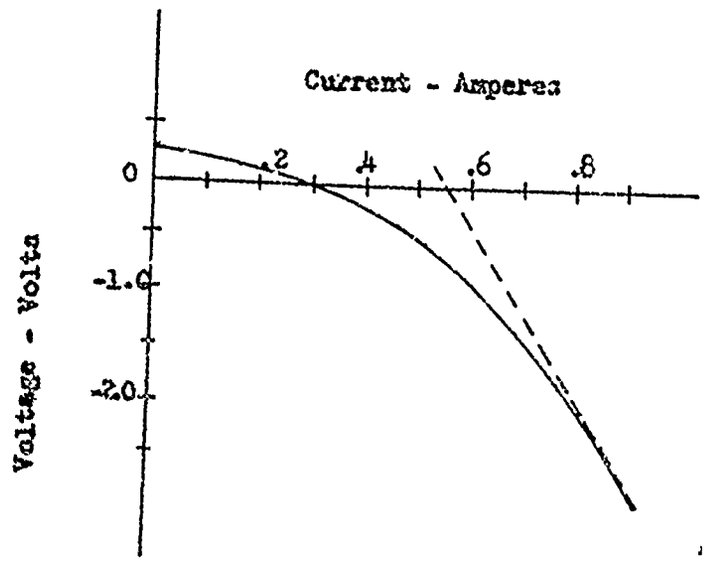

Figure 11. Current - Voltage Curve for Device #6 Reverse Bias Applied (See Table IX).

obtained is 240 ma. Since the active area of the device is 0.55 cm x 0.30 cm (See Table IX), the short circuit current collected per unit area is 1.5 amp cm^{-2}.

An attempt was made to estimate the maximum attainable short circuit current. A reverse bias was applied to the device, while it was illuminated by the 9.95 watt cm^{-2} source. The reverse characteristics appeared to approach an asymptote. (See Figure 11.) The asymptote intersected the current axis at 550 ma. This current is presumably the maximum collectable current of the device. The current collectable per unit area for the 0.55 cm x 0.30 cm device is 3.3 amp.cm^{-2}.

E. Investigation of Deficiencies in Devices

The deficiencies in the performances of the devices that have been fabricated can be attributed to any combination of the three following factors: (1) excessive bulk recombination; (2) excessive surface recombination; (3) faulty contacts. The following discussion describes how the relative importance of each of these deficiencies is evaluated.

1. Contacts deficiencies

A series of samples was prepared according to the following procedure: (1) Silicon dioxide was deposited on both sides of a polished intrinsic germanium wafer. (2) A pattern of dots was etched through the silicon dioxide on one side of the wafer. (3) An aluminum film was deposited over

half the surface on which the dot pattern had been etched. (4) Metal films for n contacts were deposited on the other half of the wafer on which the dot patterns had been etched. (5) The aluminum and n contact films were etched to form a complementary pattern to the silicon dioxide pattern. (I.e., the metal films patterns consisted of dots which covered the areas of the surface on which the silicon dioxide film had been etched.) (6) The aluminum and n contact films were alloyed simultaneously.

The open circuit voltage of the devices fabricated according to the above procedure was measured while the unprocessed surface of the device was illuminated with the 0.7 watt/cm^2 source. The testing procedure was exactly the same as that used to obtain the results shown in Table IX. The results of the measurements are summarized in Table X. The following conclusions can be drawn from these results: (1) In general the open circuit voltages obtained for devices with the arsenic-doped contacts is better than that obtained for devices without arsenic-doped contacts. (2) The open circuit voltage seems to hit an upper limiting value of 0.20 volts.

2. Lifetime damage due to silicon dioxide deposition

A series of tests was carried out to evaluate the effect of silicon dioxide deposition on the bulk and surface lifetime of devices. Three germanium strips were cut from an intrinsic wafer which had been polished on both sides. Silicon dioxide was deposited on one side of one strip and on both sides of another. Four gold contacts were then evaporated on each strip to form the type of structure shown in Figure 12. The portion of the contact on the rough edge was for the purpose of forming a good ohmic contact; and the portion of the contact on the polished

TABLE X

Open Circuit Voltage Output of Dot-Pattern Devices

Device #	Thickness of Aluminum Film (Å)	n Contact Material*	Thickness of n Contact Material Film (Å)	Alloying Temperature (°C)	Open Circuit Voltage (volts)
1	4500	Au	360	435°C	0.125
		Sb	400		
		Au	120		
2	4500	Au	360	520°C	0.17
		Sb	400		
		Au	120		
3	4500	As	130	435°C	0.195
		Sb	130		
		Au	700		
4	4500	As	130	520°C	0.20
		Sb	130		
		Au	700		
5	4500	As	200	435°C	0.20
		Sb	500		
		Au	10,000		
6	4500	As	200	435°C	0.15
		Sb	500		
		Au	3,000		
		Sb	20,000		

*The n contact films for a device are listed in the order in which they were evaporated.

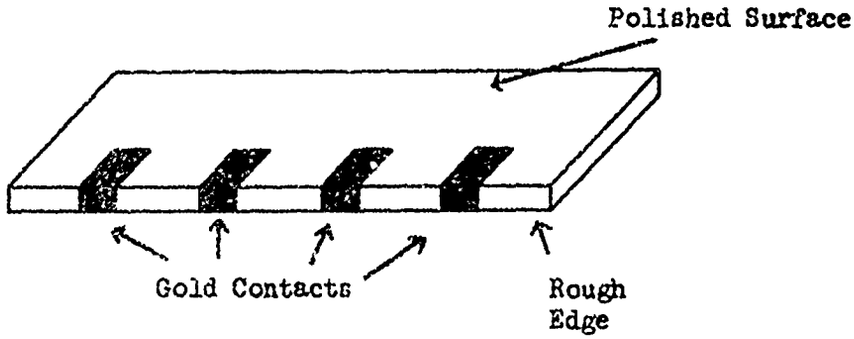

Figure 12. Sample Used to Test Effect of Silicon Dioxide Deposition on Lifetime

surface was for making contact with a probe.

The sample was illuminated, and the excess carrier concentration due to the illumination was measured by measuring the conductivity of the substrate. (See Figure 13.) Since the gold contacts were not perfectly ohmic, the conductivity was measured by a four point probe technique. A fixed current flowed through the outer probes, and the voltage drop was measured across the inner probes with a high impedance volt meter. Since the germanium substrates were intrinsic, the ratio of excess carrier concentration to intrinsic carrier concentration was given by the ratio of the voltage drop without illumination to the voltage drop with illumination.

The results of the measurements are summarized in Table XI. The test fixture and illumination source are the same as those used to obtain the results shown in Tables IX and X.

The following conclusions can be drawn from the results in Table XI: (1) The deposition of silicon dioxide appears to degrade the bulk and/or surface lifetime. (2) The silicon dioxide film enhances the absorption of useful illumination. (3) The effect of depositing silicon dioxide on both sides of the wafer is not significantly different from the effect of depositing it on one side only.

3. Determination of the dominant source of recombination

Theoretical investigations have shown that surface recombination velocity is smaller for accumulated or depleted surfaces than for flat band surfaces. An experiment was carried out in which the surface recombination velocity of a germanium substrate was varied by varying the surface potential. The substrate was prepared like the sample shown in Figure 12 with silicon dioxide films deposited on both sides.

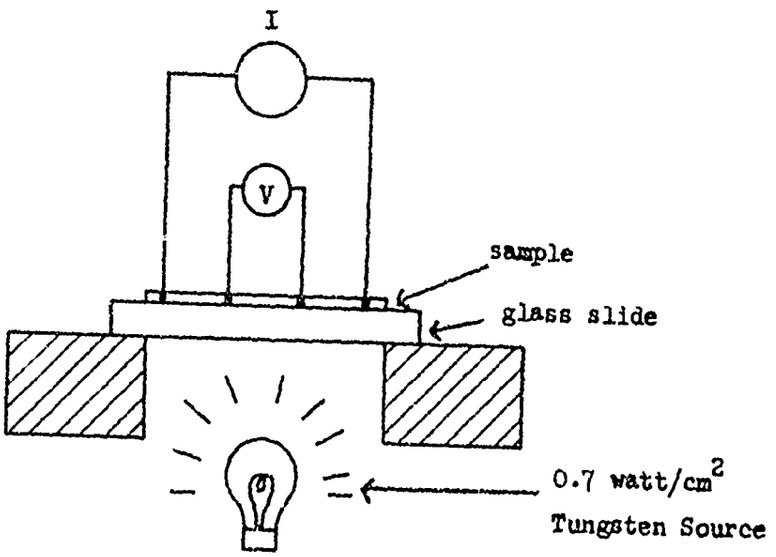

Figure 13. Apparatus Used to Test Effect of Silicon Dioxide Deposition on Lifetime

TABLE XI

Effect of Silicon Dioxide Deposition on Excess Carrier Concentration

Sample #	Description	Relative Excess Carrier Concentration (n/n_i)
1	No silicon dioxide on either side	110
2	Silicon dioxide on one side; side without silicon dioxide was illuminated	37
2	Silicon dioxide on one side; side with silicon dioxide was illuminated	46
3	Silicon dioxide on both sides	40

Transparent but electrically conducting films of aluminum were deposited on both sides of the substrate. The aluminum films were electrically isolated from the gold contacts and the germanium substrate.

The conductivity of the samples was measured with the apparatus shown in Figure 13, but with two modifications: (1) The 0.7 watt cm^2 tungsten source was replaced with a low intensity source in order to prevent heating the substrate. (2) A D.C. bias was applied to the transparent aluminum plates with respect to one of the voltage contacts.

The results of the measurements are shown in Table XII.

TABLE XII

Relative Conductivity as a Function of Surface Bias

Bias (volts)	Relative excess carrier concentration $(\frac{n}{n_i})$
10	0.11
5	0.15
0	0.22
-5	0.24
-15	0.40
-30	0.49
-41	0.72

The change in conductivity resulting from the surface charge layer induced by the bias was appropriately compensated for. The following observations can be made: (1) The rate of recombination on the surface is greater than the rate of recombination in the bulk. The excess carrier concentration at -41 volts is more than three times as great as that at 0 volts. (2) Contrary to theoretical predictions the excess carrier concentration for accumulated n-type surfaces (positive bias) does not increase with increasing bias. Furthermore the excess carrier concentration for accumulated p-type surfaces (negative bias) does not increase with increasing bias as fast as it should. Both of these effects are probably due to the drift of ions in the unannealed silicon dioxide film.

4. Conclusions

The following conclusions can be drawn from the tests which were carried out to investigate the deficiencies of the devices. (1) For devices whose open circuit output voltage is well below 0.20 volts*, the dominant deficiency is faulty contacts. (2) For devices whose open circuit voltage is nearly equal to 0.20 volts*, the dominant deficiency is excessive surface recombinations If bulk recombination was the dominant recombination mechanism, the measurements summarized in Table XIIwould have been independent of bias voltage. These conclusions can be collaborated with a mathematical expression which may be used to roughly approximate the excess carrier concentration at the junctions of a p-i-n thermophotovoltaic cell in terms of the open circuit voltage:

$$\frac{n}{n_i} = \exp \frac{eV}{2kT}$$

For V = 0.20 volts and T = 300°K, $n/n_i = 47$. This compares reasonably well with the values of 46 and 40 obtained with devices 2 and 3 in Table XI.

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*This value of open circuit voltage is for samples illuminated with the 0.7 watt cm^2 source with the same test fixture used to obtain the results in Tables IX, X, and XI.

III. CONCLUSIONS AND RECOMMENDATIONS

As we have pointed out in our description of the experimental results, the performance of the devices which were fabricated falls far short of the performance which was predicted for devices with optimum physical parameters. The primary reasons for this are:

1. High surface recombination velocity
2. High bulk recombination
3. Poor junctions

Any future program which is directed toward the improvement of p-i-n planar photovoltaic cells should take these points into consideration. The surface recombination can be reduced through appropriate annealing procedures after the deposition of the insulating film. The alloying problems which have been discussed can be solved either by using appropriate alloying techniques or by the use of ion implantation to form the n^+ and p^+ contacts. The problem with bulk recombination reduction during processing can be eliminated by using a fabrication procedure which keeps the maximum processing temperature below 300°C. In that case very little degradation should occur in the bulk lifetime.

A maximum conversion efficiency of 14.7% was computed for an optimized device operating with illumination from an 1873°K erbium oxide source. Nearly half the energy radiated from such a source is carried by photons whose energy is below that of the germanium band gap. The use of a reflective coating which will return these photons to the source can lead to significant improvement in the operating efficiency. Future work should

include the fabrication of cells which have such reflective coatings.

Little work has been done on the present study with regard to heat sinking of the device. It is necessary that such heat sinking be accomplished because of the very rapid degradation of the device characteristics with an increase in cell temperature. Heat sinking of a p-i-n planar cell is more difficult than for a standard p-n junction cell because of the fact that the electrical contacts are both on the same surface as the heat sink, and one must simultaneously obtain the electrical isolation and good thermal contact to the surface. Any future work should include a program to minimize the temperature drop across this interface.

If the above mentioned problems can be solved, and all indications are that they can, the result should be a thermolphotovoltaic cell with relatively high conversion efficiency.

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APPENDIX

In this appendix the ADOP program will be described in some detail. The input parameters and the printed output will also be described.

Description of the Program

The program is described very briefly in the flow chart shown on page 58 . First of all the input values are set and preliminary computations and initializations are made (Box A). These input values include an initial guess of the dimensions of the device for which the maximum power will occur. The input current is initially set equal to zero (Box B). After additional initial computations done in Boxes B and C, the open circuit voltage is evaluated (Boxes D, E and F). In order to evaluate the output voltage, a boundary value problem must first be solved.* This problem is solved in the computer program by successive over-relaxation. In the successive over-relaxation process an iteration (Box D) is carried out in which a new and better estimate of the solution of the boundary value problem is obtained from an original estimate. Then a convergence test is carried out to determine if the new estimate is sufficiently close to the solution of the boundary value problem. If not, the new estimate is used in the iteration process to obtain a still better estimate. By repeated iterations and convergence tests, the estimate is successively improved until the convergence test is finally passed.

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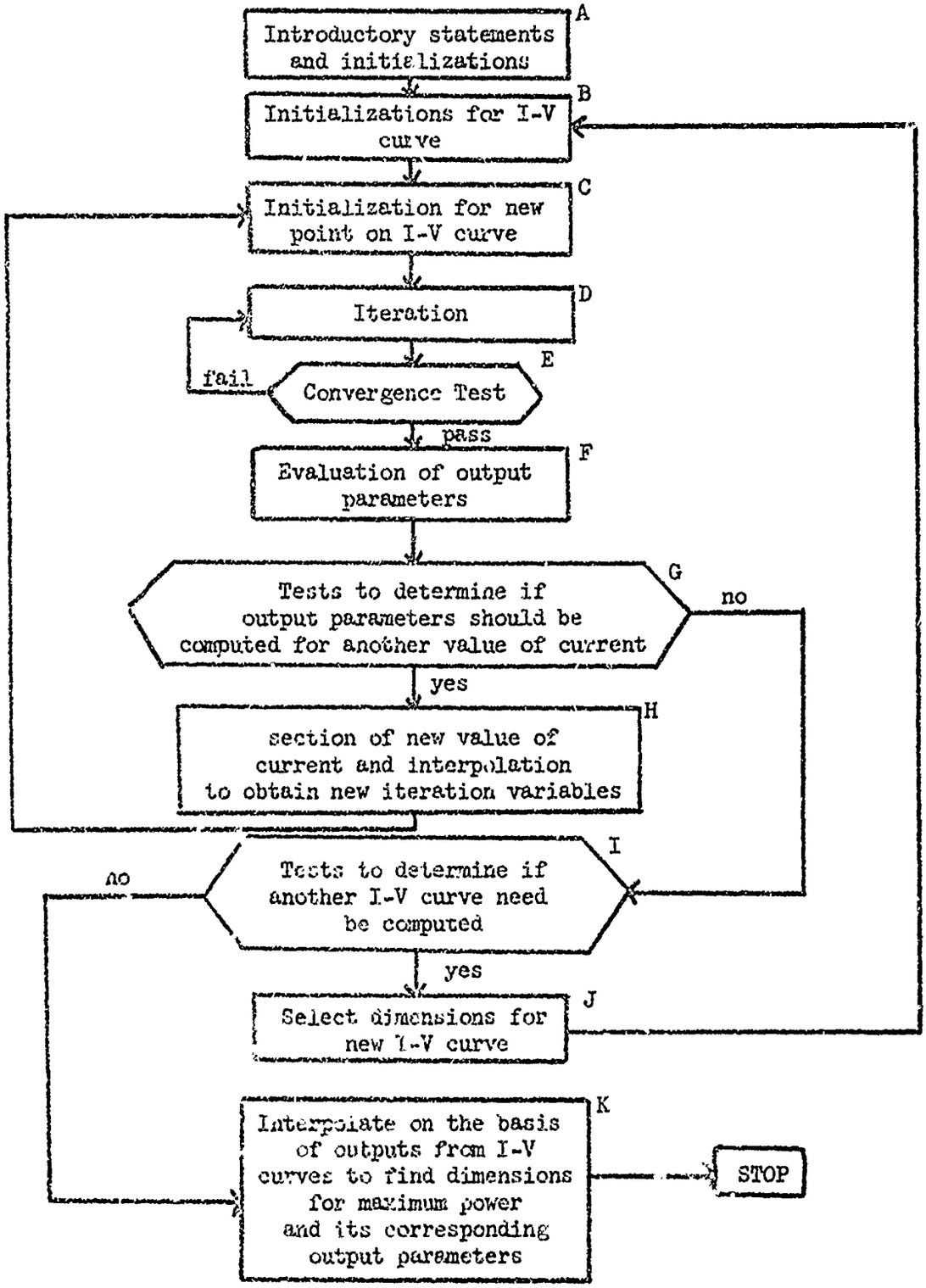
*The theoretical formulation of the boundary value problem and a detailed description of the portion of the computer program in which it is solved is included in Report No. 1[1].

ADOP PROGRAM



The solution of the boundary value problem is then used to compute the output voltage and other output parameters (Box F).

Once the open circuit voltage is computed, a new value of current is selected (Box H); and the computations made in Boxes C, D, E and F are repeated to obtain the output voltage for this current. This process of selecting new values of current and evaluating the corresponding values of voltage is repeated until a sufficient number of values are obtained to provide very good estimates of the short circuit current and the maximum power.

After it has been determined that the short circuit current and the maximum power can be satisfactorily estimated (Box G), a new set of dimensions is selected for the device (Box J). The process of obtaining enough points on the I-V curve to estimate the maximum power and the short circuit current is repeated for the new set of dimensions.

This process of selecting new dimensions and evaluating the output parameters for these dimensions is systematically repeated. The dimensions are selected in such a way that they tend to be close to those dimensions for which maximum power will occur.*

After it has been determined that the output parameters have been evaluated for a sufficient number of sets of dimensions (Box I), the maximum power and the dimensions for which maximum power will occur are determined by means of an interpolation process. A quadratic function of the form

$$P = A_o + A_1 \ell_n + A_2 \ell_p + A_3 x_o + A_{11} \ell_n^2 + A_{22} \ell_p^2 + A_{33} x_o^2 + 2A_{12} \ell_n \ell_p$$
$$2A_{13} \ell_n x_o + 2A_{23} \ell_p x_o$$

*The dimensions which are varied are the width of the n contact (ℓ_n), the width of the p contact (ℓ_p), and the thickness of the device (x_o). These dimensions must be varied in discreet increments. (See Report No. 1.)

is fitted to the values of output power associated with ten appropriately selected sets of dimensions. In the above equation P is the power output and the A's are constants. Note that since there are ten A's, ten equations (which come from the ten sets of dimensions) are needed to evaluate these A's. Once the A's are evaluated, the values of ℓ_n, ℓ_p and x_o which maximize P are determined, and finally the maximum power is obtained.

A number of other parameters (such as open circuit voltage and short circuit current) are obtained from quadratic interpotations for the dimensions at which maximum power occurs.

Input parameters

The input parameters are listed in the three catogories which are defined below: physical parameters--physical values which are needed to evaluate the performance of the device; dimension parameters--numerical values which define the dimensions of the device; program parameters--numerical values which control the speed and accuracy of the program and the amount of detail in the output.

Physical parameters

The physical parameters which are listed in statements 1650-2100 of the ADOP program are described in Table XIII. The generation rate of hole-electron pairs as a function of distance from the illuminated surface is read in at statement 4250.

TABLE XIII

LIST OF PHYSICAL PARAMETERS

FORTRAN Name	Physical Symbol(s)	Comments
KTOE	kT/e	(kT over e)
DP	D_p	hole diffusion coefficient
DN	D_n	electron diffusion coefficient
NI	ni	intrinsic carrier concentration
RCOMFAC	r	recombination factor
VSB	$V_{S.B}$	Surface recombination velocity on bottom or unilluminated surface.
VST	V_{ST}	surface recombination velocity on top or illuminated surface
VGAP	V_G	(energy gap voltage)
CURDOPT		(optimum current density) The current collected per unit area of illuminated surface if every photon capable of generating a hole-electron pair is absorbed and if every optically generated hole-electron pair is collected.

Dimension parameters

The dimension parameters which are given in statements 3100-3400 can be described concisely in the following equations:

(1) LN = 2 * NLN1 * K

(2) LP = 2 * NLP1 * K

(3) XO = NXO1 * H

(4) LI = NLI1 * K

(5) $\left\{\begin{matrix}\text{minimum} \\ \text{value of} \\ \text{XO}\end{matrix}\right\}$ = (NXOMIN + 1) * H

where

LN = width of n contact

LP = width of p contact

XO = thickness of device

The fortran variables NLN1, NLP1, NXO1, NLI1 and NXOMIN are integers. The variables H and K are real numbers which specify increment sizes in centimeters. (See Report No. 1.[1]) The dimensions are constrained to values which are integral factors of these increments. In the ADOP program the dimensions of the device are varied by systematically varying the values of NLN1, NLP1 and NXO1 (Box J of the flow chart). The initial guess of the dimensions for which maximum power occurs is determined by the initially specified values of NLN1, NLP1 and NXO1.

In some cases the optimum thickness of a device will be much thinner than the minimum thickness attainable in practice due to limitations in technology. Therefore the program has been adapted to optimize the device under the constraint that XO will have a specified minimum attainable value. This value can be specified by appropriately choosing NXOMIN and H in equation (5).

The time required to run the ADOP program can be reduced by choosing the largest possible values for H and K[1]. On the other hand, the accuracy

of results obtained increases with decreasing values of H and K.[1] Experimental runs were carried out for which the physical parameters and the device dimensions were held constant as H and K were varied. The error in the value of maximum power was made negligible by choosing sufficiently small values of H and K. The error in the value of maximum power obtained for larger values of H and K could then be estimated by comparing the maximum power obtained with larger values of H and K with that obtained with the small values of H and K. For values of H and K used to obtain the results in Tables I through VI the estimated error is 1% or less.

Program parameters

A discussion of program parameters is of little value unless one wishes to use the program. In this case a detailed description of the program will be needed. A document providing such a description will be prepared at a later date.

Printed output

Table XIV lists and describes the FORTRAN variables that appear in the printed output in the order in which they appear.

The printout can be divided into two parts. The first part gives the output for a given set of dimensions. (See Table XV) This part will be repeated for each set of dimensions for which the points on an I-V plot are to be obtained. The second part summarizes the outputs which are computed for each set of dimensions and gives information which will describe the output of the optimized device. (See Table XVI)

Output for a given set of dimensions.-- The values of CURDNET, VOLTAGE and ETA for the points on the I-V curve are listed in part [B]

TABLE XIV

List of Output Parameters

Fortran variable	Description
ILE	(index of linear equations) A subroutine is used which solves a simultaneous system of linear equations. If ILE=0, the system is solved satisfactorily. Otherwise the system is singular to the accuracy of the computer.
PTKNT	(point count) an index which is chronologically associated with a point on the I-V plot.
CURDNET	(current density net) net current output per unit area of illuminated surface.
VOLTAGE	voltage output which is associated with a given value of CURDNET.
ETA	cell efficiency associated with a given pair of valves of VOLTAGE and CURDNET, i.e. ETA= CURDNET * VOLTAGE/CURDMAX/VGAP.
VOC	(open circuit voltage)
VF	(voltage factor) i.e. VF = VOC/VGAP.
CURDSC	(short circuit current density) The short circuit current produced per unit area of illuminated surface.
ETACOL	(collection efficiency) i.e. ETACOL = CURDSC/CURDMAX.
PMAXPOW	(maximum power point power)

JMAXPOW	(maximum power point current) The current per unit area of illuminated surface at the maximum power point.
VMAXPOW	(maximum power point voltage)
CF	(curve factor) i.e. CF = PMAXPOW/VOC/CURDSC.
ETACELL	(cell efficiency) i.e. ETACELL = PMAXPOW/POWMAX.
XO	the thickness of the photovoltaic cell.
LN	width of the n contact
LP	width of the p contact
LI	spacing between contacts.
H, K	increment sizes
CURDOPT	optimum current density; the current collected per unit area of illuminated surface if every photon capable of generating a hole-electron pair is absorbed and if every optically generated hole-electron-pair is collected.
ISE	(index of symmetrical equations) A subroutine is used which solves the simultaneous system of equations whose coefficient matrix must be positive definite or negative. If ISE=0, the system is solved satisfactorily. Otherwise the coefficient matrix is either singular to computer accuracy or is not positive or negative definite.

ID	(index of dimensions) an index which is chronologically associated with a set of dimensions for which the points for an I-V plot are obtained.
ETAC	same as ETACOL
ETACE	same as ETACELL
CURDMAX	(maximum current density) the current output per unit area of illuminated cell when all generated hole-electron pairs are collected.
POWMAX	(maximum attainable power) the power output per unit area of illuminated surface when all the generated hole-electron pairs are collected with an output voltage equal to the energy gap voltage. I.e. POWMAX= CURDMAX * VGAP.
ETAABS	(CURDMAX/CURDOPT) the ratio of the number of carriers generated in the finite thickness device to the number of carriers generated in an infinitly thick device.

TABLE XV

Printed Output for a Given Set of Dimensions

[D]	[E]	[F]
43	1.318E+17	1.318E+17
44	1.164E+17	1.162E+17
21	9.904E+16	9.873E+16
20	7.869E+16	7.823E+16
25	5.249E+16	5.187E+16
34	1.714E+16	1.640E+16
51	5.758E+15	4.981E+15
ILE =0		
45	3.340E+16	3.270E+16
ILE =0		
ILE =0		
54	2.480E+15	1.690E+15
21	1.379E+15	5.823E+14
30	1.001E+15	2.023E+14
20	8.708E+14	7.079E+13
20	8.251E+14	2.473E+13

[A]

PTKNT	CURDNET	VOLTAGE	ETA
1	0.	4.439E-01	0.
2	8.089E-01	4.372E-01	1.325E-01
3	1.618E+00	4.284E-01	2.596E-01
4	2.427E+00	4.159E-01	3.780E-01
5	3.236E+00	3.935E-01	4.770E-01
6	3.892E+00	3.286E-01	4.791E-01
7	3.992E+00	2.548E-01	3.811E-01
8	3.654E+00	3.680E-01	5.038E-01
9	4.011E+00	1.830E-01	2.750E-01
10	4.016E+00	1.171E-01	.762E-01
11	4.017E+00	6.494E-02	9.774E-02
12	4.018E+00	2.676E-02	4.028E-02
13	4.018E+00	8.595E-04	1.294E-03

[B]

VOC	=	.4439
VF	=	.6726
CURDSC	=	4.018E+00
ETACOL	=	.9935
PMAXPOW	=	1.345E+00
CMAXPOW	=	3.664E+00
VMAXPOW	=	.3670
CF	=	.7539
ETACELL	=	.5038
XO	=	5.000E-02
LN	=	1.500E-02
LP	=	2.500E-02
LI	=	2.500E-03

[C]

TABLE XVI

Summary of Outputs for Given Sets of Dimensions and Output for Optimized Device

2.570E+00	3.936E+00	4.012E+00	[A]
-8.625E-04	4.472E-04	-5.768E-06	
4.472E-04	-5.112E-04	6.543E-06	
-5.768E-06	6.543E-06	-5.032E-03	
-6.851E-04	3.196E-04	1.189E-04	

-2.063E-04	-1.167E-03	-5.032E-03	[B]
5.632E-01	8.263E-01	4.473E-04	
8.263E-01	-5.632E-01	-2.187E-03	
1.555E-03	-1.601E-03	1.000E+00	

H = 1.000E-02 K = 2.500E-03 LI = 2.500E-03 CURDOPT = 5.000E+00 ISE = 0

ID	LN	LP	XO	VOC	VF	CURDSC	ETAC	CURIMAX	CMAXPOW	VMXPW	PMAXPOW	CF	ETACE
1	3	4	4	.4494	.6809	3.934E+00	.9964	3.948E+00	3.611E+00	.3738	1.350E+00	.7635	.5180
2	2	4	4	.4494	.6809	3.935E+00	.9967	3.9[illegible]3E+00	3.610E+00	.3738	1.350E+00	.7632	.5179
3	4	4	4	.4494	.6809	3.933E+00	.9960	3.948E+00	3.609E+00	.3737	1.348E+00	.7629	.5174
4	3	3	4	.4494	.6809	3.933E+00	.9960	3.948E+00	3.610E+00	.3738	1.349E+00	.7634	.5177
5	3	5	4	.4494	.6809	3.935E+00	.9967	3.948E+00	3.611E+00	.3738	1.350E+00	.7632	.5179
6	3	4	3	.4563	.6913	3.815E+00	.9985	3.820E+00	3.522E+00	.3818	1.345E+00	.7726	.5333
7	3	4	5	.4439	.6726	4.016E+00	.9931	4.044E+00	3.664E+00	.3671	1.345E+00	.7543	.5039
8	2	5	4	.4494	.6809	3.935E+00	.9966	3.948E+00	3.609E+00	.3737	1.349E+00	.7627	.5175
9	2	4	5	.4439	.6726	4.018E+00	.9935	4.044E+00	3.664E+00	.3671	1.345E+00	.7539	.5038
10	3	5	5	.4439	.6726	4.018E+00	.9935	4.044E+00	3.664E+00	.3670	1.345E+00	.7539	.5038

[D]

LN	= 1.285E-02
LP	= 1.968E-02
XO	= 4.012E-02
VOC	= .4493
VF	= .6808
CURDSC	= 3.936E+00
ETACOL	= .9965
CURIMAX	= 3.950E+00
CMAXPOW	= 3.612E+00
VMAXPOW	= .3738
PMAXPOW	= 1.350E+00
POWMAX	= 2.607E+00
CF	= .7634

[E]

or Table XV. The column labled PTKNT lists indices which are chronologically assigned to each set of values CURDNET, VOLTAGE and ETA.

In part [A] the reader will note that there are ten rows of numbers excluding the rows containing the expression, ILE = 0. Each of these rows corresponds to a row in part [B] with the first row in [A] corresponding to the first row in [B], the second row in [A] with the second row in [B], etc. The column designated by [D] gives the number of iterations required for convergence. The column designated by [E] gives the excess carrier concentrations in the middle of the n contact. The column designated by [F] gives the excess carrier concentration in the middle of the p contact.

The expressions ILE = 0 result from a curve fitting routine which is used to estimate the value of CURDNET for which the maximum power will occur. (See Table XIV..)

In part [C] the output parameters and dimensions of the cell are listed.

Summary of outputs for each set of dimensions and output of optimized device.-- The cell dimensions for which output parameters have been computed and the corresponding output parameters are summarized in part [D] of Table XV. The columns headed by LN and LP list half the number of increments on the n and p contacts, and the column headed by XO lists the number of increments along the dimension of the device that is perpendicular to the illuminated surface. (The values listed under LN, LP and XO are equal to the values NLN1, NLP1 and NXO1 described on page 62). Note that the row of values corresponding to the number 9 in the column headed by ID is obtained from Table XV.

The list of values in part [E] of Table XVI gives the dimensions and output parameters of the optimally designed device.

The array of points shown in part [B] of Table XVI may be represented algebraically by the array shown below:

λ_1	λ_2	λ_3
$v_{1\ell n}$	$v_{1\ell p}$	v_{1xo}
$v_{2\ell n}$	$v_{2\ell p}$	v_{2xo}
$v_{3\ell n}$	$v_{3\ell p}$	v_{3xo}

This array consists of the eigenvalues and orthonormal eigenvectors of the symmetric matrix with elements A_{ij}. The power may be expressed in the equation:

$$P = P_{MAXPOW} + \lambda_1 v_1^2 + \lambda_2 v_2^2 + \lambda_3 v_3^2$$

where $v_i = v_{i\ell n} (n_{\ell n} - \bar{n}_{\ell n}) + v_{i\ell p} (n_{\ell p} - \bar{n}_{\ell p}) + v_{ixo} (n_{xo} - \bar{n}_{xo})$

for i = 1, 2 and 3.

```
      PROGRAM MAIN (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C                                                                       200
      REAL LN,LP,LI,NSINITL,NO,K,M,MDPEDK,MAGIDUM,MAGIMAX,NI,NOPPO,NSMAX  300
     1,KTOE,NN,NP,JUNCPOT,LNJOMJ,NST2,NO2,NS4,NO4,KO2DNEH,KO2DPEH,EL(200 400
     2),W(200),X(200),Y(200),Z(200),CRNT(100),VOLT(100),NSI(22,49),NS2(2 500
     32,49),NS3(22,49),MAGI1(22,49),MAGI2(22,49),MAGI3(22,49),NS(22,49), 600
     4MAGI(22,49),DUMMY(22,49),DUMAG(22,49),DNDT(22,49),NEI(22,49),CURDX 700
     5(49),CURDY(49)                                                    800
      REAL NSBAR,NSSBAR,NI2,GBULK(22)                                   830
      REAL NCINC,N1,N2,N3,NSRF                                          860
      INTEGER R,S,RH,SH,RP1,SP1,RHP1,SHP1                               900
      INTEGER RH2                                                       1000
      INTEGER RI,RIM1,SIP1,SI                                           1100
      INTEGER PATHKNT,PATHNMB                                           1200
      INTEGER PTKNT                                                     1300
      REAL NLN,NLP,NXO,NLI,VOCD(50),VFD(50),CURDSCD(50),ETACOLD(50),    1303
     1PMXPOWD(50),CMXPOWD(50),VMXPOWD(50),CFD(50),ETAD(50),CURDMXD(50)  1330
      DIMENSION XM(3,1),EIGVAL(3)                                       1390
      DIMENSION CUMGEN(82)                                              1350
      COMMON IET,JLNP,JLNM,JLPP,JLPM,JXOP,JXOM,LNLP,LNXO,LPXO,RICLN,    1400
     1RICLP,RICXO,BM(3,1),AM(3,3),JNLNT(50),JNLP(50),JNXO(50),ID       1450
C                                                                       1500
C     LISTING OF PHYSICAL PARAMETERS                                    1550
C                                                                       1600
      KTOE=0.0259                                                       1650
      DP=48.0                                                           1700
      DN=96.0                                                           1750
      NI=2.5E13                                                         1800
      PO=NI                                                             1850
      RCOMFAC=2.8E-14                                                   1900
      VSB=100.                                                          1950
      VST=100.                                                          2000
      VGAP=0.65                                                         2050
      CURDOPT=1.                                                        2100
C                                                                       2150
C     LISTING OF PROGRAM PARAMETERS                                     2200
C                                                                       2250
      IC=2                                                              2300
      MESHNMB=1                                                         2350
      II=2                                                              2400
      LL=0                                                              2450
      IMAX=150                                                          2500
      ICORMIN=20                                                        2550
      IITVAR =1                                                         2600
      IPATH=1                                                           2650
      ICURVE=0                                                          2700
      EPSILON=0.001                                                     2750
      NCINC=5.0                                                         2800
      RF=0.35                                                           2850
      FACTOR=5.0                                                        2900
C                                                                       2950
C     LISTING OF DIMENSION PARAMETERS                                   3000
C                                                                       3050
      INF=NI N1=6                                                       3100
      NT=NPN1=10                                                        3150
      NJ=NXO1=4                                                         3200
      NMI=2                                                             3250
      NII=NLI+1                                                         3300
      EPS=.125E-2*NLP.                                                  3350
      EPS=0.25E-2                                                       3400
```

```
C
C LISTING OF RELAXATION FACTORS
C
      OMEGAB=1.92
      OMEGAS=1.4
      OMEGABH = 1.92
      OMEGASB=0.9
      OMEGAST=1.4
       OMEGAC=1.4
      OMEGACH=1.4
C
C EVALUATION OF SCALE FACTOR AND READIN AND SCALING OF CUMGEN
C
      READ(5,685) CJRDSCL
      SCALE=CURDOPT/CJRDSCL
      DO 3   NX=1,82
      READ(5,685) CJMGEN(NX)
      CUMGEN(NX)=CJMGEN(NX)*SCALE
      GSURF=CUMGEN(2)-CUMGEN(1)
C
C LISTING OF FIXED CONSTANTS AND PRELIMINARY COMPUTATIONS
C
      NU=LMAX-LH
      ALPHA=2.0*DN*DP/(DN+DP)
      PC=NI*NI/PC
      NOPPO=NC+PO
      POPNO=PC+NO
      POPNO2=POPNO+POPNO
       D2=PO+PO
      PO4=PO2+PO2
      NO2=NO+NO
      NO4=NO2+NO2
       ECC=(PC+NC)/2.
      NUMC=(DP*PO+DN*NO)/(DP+DN)
      NI2=NI+NI
       D=0
      IT=IC
      NOPTS=0
      NOXXOM=3
C
C BEGIN LOOP FOR EVALUATION OF POINTS ON I-V CURVE
C
       D=ID+1
       LN=NLN1
       LP=NLP1
       NX=NX01
      NLNITL=NLN1+NLP1+NLI1
       INITL=NX01
      LN=NLN*K*2.0
       P=NLP*K*2.0
         =NLI*K
       =NX0*H
      DRONET=0.0
      JR=N/12.5E-4+0.5
       =GEN=CUMGEN(NX01*N(H+2)-CUMGEN(2)
       =NI=1
      NOCL,4=1
      CURDMAX=(GSURF+BULKGEN)*1.6e-19
      COMMAX=CURDMAX*VGAP
      ND=(LP+1)/2.0+LI
      COOS=ALPHA*EPSILON/(XD*XD+YD*YD)
```

```
C
C     LISTING OF TERMS THAT MUST BE RESET FOR NEW VALUES OF CURDNET
C
   10 I=IINITL
      J=JINITL
      MESHKNT=1
C
C     VALUE OF INDXITL SET TO CAUSE INITIALIZATION
C
      INDXITL=0
C
C     EVALUATE I AND J DEPENDENT TERMS
C
C     COMPUTATION OF INCREMENT SIZES
C
   30 REALI=I
      H=XO/REALI
      REALJ=J
      K=((LN+LP)/2.+LI)/REALJ
C
C     COMPUTATION OF INCREMENT DEPENDENT VARIABLES
C
      AK=ALPHA/(K*K)
      AH=ALPHA/(H*H)
      HO2DNE=H/2.0/DN/1.6E-19
      HO2DPE=H/2.0/DP/1.6E-19
      MDPEOK=-DP*1.6E-19/K
      H2=2.0*H
      DNEOK=DN*1.6E-19/K
      AH2PAK2=2.0*AH+2.0*AK
      R2=2.0*RCOMFAC
      HSOKS=H*H/K/K
      HSOKSP1=HSOKS+1.0
      HOATGS=H/ALPHA*GSURF
      DP2EKOH=DP*2.0*1.60E-19*K/H
      DN2EKOH=DN*2.0*1.6E-19*K/H
      KO2DNEH=K/2.0/DN/1.6E-19/H
      KO2DPEH=K/2.0/DP/1.6E-19/H
      HO2DNEK=H/2.0/DN/1.6E-19/K
      HO2DPEK=H/2.0/DP/1.6E-19/K
      HVSTO2A=H*VST/2.0/ALPHA
      HVSBO2A=H*VSB/2.0/ALPHA
C
C     LISTING OF ITERATION INDICES
C
      RH=LN/(2.*K)+0.5
      SH=(LN/2.+LI)/K+1.5
      S=SH
      RHP1=RH+1
      R=RHP1
      SHP1=SH+1
      RP1=R+1
      SP1=S+1
      JH=J+1
      JN=J+2
      IH=I+2
      IN=IH
      JHM1=JH-1
      JNM1=JN-1
      INM1=IN-1
      IHM1=IH-1
```

```
      LISTING OF TERMS DEPENDENT ON ITERATION INDICES

      SMR=S-R
      RJNM2=JN-2
      TERM1=N1+(VST+VSB*SMR/RJNM2)/R2/XO
      TERM2=VST/R2/XO/RJNM2
      TERM3=VSB/R2/XO/RJNM2
      BULKPTS=(IN-2)*(JN-2)

      EVALUATION OF GBJLK

      ICJ=I*NIH+2
      DO 35   NX=2,INM1
      ICL=ICJ-NIH
      GBJLK(NX)=(CJMGEN(ICJ)-CJMGEN(ICL))/H
      ICJ=ICL

      LISTING OF TESTPOINT INDICES

      INDXXC=(IN+2)/2
      INDXYC=(JN+2)/2
      INDXXF=IN-1
      INDXNN=R
      INDXPN=SP1

      LISTING OF TERMS THAT MUST CHANGE WITH EACH NEW VALUE OF CURDNET

      GBADXOR=(GSJRF*BJLKGEN-CJRDNET/1.6E-19)/XO/RCOM*AC
      NSINITL=-(TERM1+SQRT(TERM1*TERM1+GBADXOR))

      INITIALIZATION OF MAGI AND NS

      IF(INDXITL.NE.0)  GO TO 45
      INDXITL=1
      IP2=I+2
      JP2=J+2
      DO 20  NX=1,IP2
      DO 20  NY=1,JP2
      MAGI(NX,NY)=0.0
20    NS(NX,NY)=NSINITL
      NSMAX=FACTOR*(-NI+SQRT(NI*NI+GBADXOR))

      BOUNDARY CONDITIONS ON MAGI ON THE BACK SURFACE AND ON CONTACTS

40    MAGIMAX=CJPMAX*((IN+2)/2.0+L)
      DO 50  NY=RP1,SP
50    MAGI(2,NY)=MAGIMAX
      DELTAIB=OMEGA/(1.+2P/R2+R2*(NSMAX+AP))
      DELTAIC=OMEGAC/(NEGAC*DELTAIB)

      RESET LOOPCNT = 0

      LOOPCNT=0

      WRITE(6,543)
      WRITE(6,544)
      DO 70 NX=1,IN
```

```
   70 WRITE (6,550) (NS(NX,NY),NY=1,JM)
      WRITE (6,560)
      DO 80 NX=2,IH
   80 WRITE (6,550) (MAGI(NX,NY),NY=1,JH)
      WRITE (6,560)
      IF((LOOPKNT.GE.LMAX).AND.(INDXETA.EQ.1)) GO TO 228
   90 IF(LOOPKNT.GE.LMAX) GO TO 515
      LOOPKNT=LOOPKNT+1
C
C     P CONTACT--APPROXIMATION OF MAGI AND NS, AND EVALUATION OF W AND Y
C
      IF(SP1.EQ.JNM1)  NS(1,SP1)=NS(2,SP1)
     1+H02DPEK*(MAGI(2,SHP1)-MAGI(2,SH))
      IF(SP1.EQ.JNM1)  GO TO 115
      W(SH)=0.0
      Y(SP1)=1.0
      DO 100 NY=SHP1,JHM1
      NST2=NS(2,NY)+NS(1,NY)
      GP=DP2EKOH*(NST2+POPNO)/(NST2+NO2)
      NS4=NS(2,NY+1)+NS(2,NY)+NS(1,NY+1)+NS(1,NY)
      GN=K02DNEH*(NS4+PO4)/(NS4+PO2PNO2)
      MAGI(2,NY)=MAGI(2,NY-1)-GP*(NS(2,NY)-NS(1,NY))
      W(NY)=W(NY-1)+GP*Y(NY)
      NS(1,NY+1)=NS(1,NY)-GN*(3.0*(MAGI(3,NY)-MAGI(2,NY))-(MAGI(4,NY)-MA
     1GI(3,NY)))-(NS(2,NY+1)-NS(2,NY))
  100 Y(NY+1)=Y(NY)+(GN+GN+GN)*W(NY)
C
C     P CONTACT--EVALUATION OF DELTA
C
      NST2=NS(2,JNM1)+NS(1,JNM1)
      GP=DP2EKOH*(NST2+POPNO)/(NST2+NO2)
      DELTA=(MAGI(2,JH)-MAGI(2,JHM1)+GP*(NS(2,JNM1)-NS(1,JNM1)))/(K(JHP
     1)+GP*Y(JNM1))
C
C     P CONTACT--EVALUATION OF MAGI AND NS
C
      DO 110 NY=SHP1,JHM1
      MAGI(2,NY)=MAGI(2,NY)+W(NY)*DELTA
  110 NS(1,NY)=NS(1,NY)+Y(NY)*DELTA
      NS(1,JNM1)=NS(1,JNM1)+Y(JNM1)*DELTA
C
C     NCONTACT--APPROXIMATION OF MAGI AND NS, AND EVALUATION OF W AND Y
C
  115 IF(R.EQ.2) NS(1,2)=NS(2,2)-K02DNEK*(MAGI(2,2)-MAGI(1,2))
      IF(R.EQ.2) GO TO 135
      W(1)=0.0
      Y(2)=1.0
      DO 120 NY=2,IH
      NST2=NS(2,NY)+NS(1,NY)
      GN=DN2EKOH*(NST2+POPNO)/(NST2+NO2)
      NS4=NS(2,NY+1)+NS(2,NY)+NS(1,NY+1)+NS(1,NY)
      GP=K02DPEH*(NS4+PO4)/(NS4+PO2PNO2)
      MAGI(2,NY)=MAGI(2,NY-1)+GN*(NS(2,NY)-NS(1,NY))
      W(NY)=W(NY-1)-GN*Y(NY)
      NS(1,NY+1)=NS(1,NY)+GP*(3.0*(MAGI(3,NY)-MAGI(2,NY))-(MAGI(4,NY)-M
     1AGI(3,NY)))+(NS(2,NY+1)-NS(2,NY))
  120 Y(NY+1)=Y(NY)-(GP+GP+GP)*W(NY)
C
C     N CONTACT--EVALUATION OF DELTA
C
      NST2=NS(2,R)+NS(1,R)
```

```
      GN=DN2EKOH*(NST2+POPNO)/(NST2+PO2)
      DELTA=(MAGI(2,RHP1)-MAGI(2,RH)-GN*(NS(2,R)-NS(1,R)))/(W(RH)-GN*Y(R
     1))

      N CONTACT--EVALJATION OF MAGI AND NS


      DO 130 NY=2,RH
      MAGI(2,NY)=MAGI(2,NY)+W(NY)*DELTA
  130 NS(1,NY)=NS(1,NY)+Y(NY)*DELTA
      NS(1,R)=NS(1,R)+Y(R)*DELTA

      NS IN INTERIOR REGION


   15 DELTAT=DELTATC
      DO 150 NX=2,INM1
      DO 140 NY=2,JNM1
      DNDT(NX,NY)=AH*(NS(NX+1,NY)-NS(NX,NY)-NS(NX,NY)+NS(NY-1,NY))+AK*(N
     1S(NX,NY+1)-NS(NX,NY)-NS(NX,NY)+NS(NX,NY-1))+GBULK(NX)-RCOMFAC*NS(N
     2X,NY)*(NS(NX,NY)+NOPPO)
      NS(NX,NY)=NS(NX,NY)+DNDT(NX,NY)*DELTAT
      IF (NS(NX,NY).LT.1.0) NS(NX,NY)=1.0
  140 IF (NS(NX,NY).GE.NSMAX) NS(NX,NY)=NSMAX
  150 DELTAT=DELTATB

      EVALJATION OF NEI


      DO 160 NX=2,INM1
      DO 160 NY=2,JNM1
  160 NEI(NX,NY)=1.0/(NS(NX,NY)+ACCC)

      MAGI IN INTERIOR REGION


      OMEGAH=OMEGACH
      DO 170 NX=3,IHM1
      NXP1=NX+1
      NXM1=NX-1
      DO 170 NY=2,JHM1
      NYP1=NY+1
      MAGIOJM=((NEI(NX,NYP1)+NEI(NX,NY))*MAGI(NXP1,NY)+(NEI(NXM1,NYP1)+N
     1EI(NXM1,NY))*MAGI(NXM1,NY)+FOURS*((NEI(NX,NYP1)+NEI(NXM1,NYP1))*MA
     2GI(NX,NYP1)+(NEI(NX,NY)+NEI(NXM1,NY))*MAGI(NX,NY-1)))/(FSOKSPL*(NE
     3I(NX,NYP1)+NEI(NXM1,NYP1)+NEI(NX,NY)+NEI(NXM1,NY))+
      MAGI(NX,NY)=MAGI(NX,NY)+OMEGAH*(MAGIOJM-MAGI(NX,NY))
  170 OMEGAH=OMEGABH

      NS AT TOP SURFACE


      DO 180 NY=2,JNM1
      M=NS(INM1,NY)+HDATGS-HVST02A*(NS(INM1,NY)+NS(IN,NY))
  180 NS(IN,NY)=NS(IN,NY)+OMEGAST*(M-NS(IN,NY))

      NS AT BOTTOM SURFACE


      IF (RP1.GT.5) GO TO 200
      DO 190 NY=2,JNM1
      M=NS(2,NY)+HDATGS-HVST02A*(NS(1,NY)+NS(2,NY))
  190 NS(1,NY)=NS(1,NY)+OMEGAST*(M-NS(1,NY))

      NS AT LEFT SIDE


      DO 210 NY=2,JN
```

```
      M=NS(NX,2)                                                        2960
  210 NS(NX,1)=NS(NX,1)+OMEGAS*(M-VS(NX,1))                             2970
C                                                                       2980
C     NS AT RIGHT EDGE                                                  2990
C                                                                       3000
      DO 220 NX=1,IN                                                    3010
      M=NS(NX,JNM1)                                                     3020
  220 NS(NX,JN)=NS(NX,JN)+OMEGAS*(M-VS(NX,JN))                          3030
C                                                                       3040
C     EVALUATION OF DELTANS AND RESET OF VALUE OF NS                    3050
C                                                                       3060
      SUM=0.0                                                           3070
      SUMS=0.0                                                          3080
      DO 222  NX=2,INM1                                                 3090
      DO 222  NY=2,JNM1                                                 3100
      SUM=SUM+NS(NX,NY)                                                 3110
  222 SUMS=SUMS+NS(NX,NY)*NS(NX,NY)                                     3120
      NSBAR=SUM/BJLKPTS                                                 3130
      NSSBAR=SUMS/BJLKPTS                                               3140
      SIGMANT=0.0                                                       3150
      DO 223  NY=2,JNM1                                                 3160
  223 SIGMANT=SIGMANT+NS(IN,NY)+NS(INM1,NY)                             3170
      SIGMANB=0.0                                                       3180
      IF(RP1.GT.S)  GO TO 225                                           3190
      DO 224  NY=RP1,S                                                  3200
  224 SIGMANB=SIGMANB+NS(2,NY)+NS(1,NY)                                 3210
  225 BO2=NSBAR+TERM1                                                   3220
      C=NSSBAR+TWO*NSBAR+TERM2*SIGMANT+TERM3*SIGMANB-GBAOXOR            3230
      IF((BO2*BO2).LT.C)  GO TO 515                                     3240
      DELTANS = - BO2 + SQRT( BO2*BO2 - C )                             3250
      DO 226  NX = 1,IN                                                 3260
      DO 226  NY = 1, JN                                                3270
  226 NS(NX,NY)=NS(NX,NY)+DELTANS                                       3280
C                                                                       3290
C     ENSURE THAT ENOUGH ITERATIONS HAVE TAKEN PLACE FOR STABILIZATION  3300
C                                                                       3310
      IF (LOOPKNT.LT.LOOPMIN) GO TO 60                                  3320
C                                                                       3330
C     CONVERGENCE TEST                                                  3340
C                                                                       3350
      AERRNS=AERRS*NSINITL                                              3360
      IF(AERRNS.LT.ABS(CNDT(2,INDXNN)))  GO TO 60                       3370
      IF(AERRNS.LT.ABS(CNDT(2,INDXPN)))  GO TO 60                       3380
      IF(AERRNS.LT.ABS(CNDT(INDXXE,INDXYC)))  GO TO 60                  3390
      IF(AERRNS.LT.ABS(CNDT(INDXXC,INDXYC)))  GO TO 60                  3400
C                                                                       3410
C     WRITEOUT FOR SUCCESSFUL EXIT                                      3420
C                                                                       3430
      IF(ITVAR.EQ.1)  GO TO 250                                         3440
      WRITE (6,540)                                                     3450
      WRITE (6,570) MESHCNT,LOOPCNT                                     3460
      WRITE (6,550)                                                     3470
      DO 230 NX=1,IN                                                    3480
  230 WRITE (6,590) (NS(NX,NY),NY=1,JN)                                 3490
      WRITE (6,560)                                                     3500
      DO 240 NX=2,IN                                                    3510
  240 WRITE (6,590) (PHI(NX,NY),NY=1,JN)                                3520
      WRITE (6,580)                                                     3530
C                                                                       3540
C     CALCULATION OF TERMS RELATED TO OUTPUT VOLTAGE AND POWER          3550
C                                                                       3560
```

```
 50 PATHNMB=R-1                                                          34100
    KN=R                                                                 34200
    KP=SP1                                                               34300
    KX=2                                                                 34400
    DO 310 PATHKNT=1,PATHNMB                                             34500
                                                                         34600
    EVALUATION OF EXCESS CARRIER CONCENTRATIONS AT JUNCTIONS             34700
                                                                         34800
    NN=(NS(2,KN)+NS(1,KN))/2.0                                           34900
    NP=(NS(2,KP)+NS(1,KP))/2.0                                           35000
    IF(IPATH.EQ.1)  GO TO 255                                            35050
    WRITE (6,580) MESHKNT,PATHKNT                                        35100
    WRITE (6,550) NN,NP                                                  35200
    CONTINUE                                                             35230
    IF(KN.EQ.2)  WRITE(6,610)  LOOPKNT,NN,NP                             35260
    IF ((NN.GT.0.0).AND.(NP.GT.0.0)) GO TO 260                           35300
    IF ((MESHKNT.EQ.MESHNMB).AND.(KN.EQ.2)) GO TO 515                    35400
    GO TO 300                                                            35500
                                                                         35600
    INITIAL POINTS IN THE GRAPHICAL INTEGRAL ALONG THE X AXIS            35700
                                                                         35800
260 PTNE=(NN+NS(2,KN))/2.0+ACCC                                          35900
    PTDHDY=(3.0*(MAGI(2,KN)-MAGI(2,KN-1))/K+(MAGI(3,KN)-MAGI(3,KN-1))/   36000
   1K)/4.0                                                               36100
    GIXN=PTDHDY/PTNE*H/2.0                                               36200
    PTNE=(NP+NS(2,KP))/2.0+ACCC                                          36300
    PTDHDY=(3.0*(MAGI(2,KP)-MAGI(2,KP-1))/K+(MAGI(3,KP)-MAGI(3,KP-1))/   36400
   1K)/4.0                                                               36500
    GIXP=PTDHDY/PTNE*H/2.0                                               36600
                                                                         36700
    EVALUATION OF GRAPHICAL INTEGRALS ALONG THE X AXIS                   36800
                                                                         36900
    IF (KX.LT.3) GO TO 280                                               37000
    DO 270 NX=3,KX                                                       37100
    PTNE=(NS(NX-1,KN)+NS(NX,KN))/2.0+ACCC                                37200
    PTDHDY=(MAGI(NX,KN)-MAGI(NX,KN-1))/K                                 37300
    GIXN=GIXN+PTDHDY/PTNE*H                                              37400
    PTNE=(NS(NX-1,KP)+NS(NX,KP))/2.0+ACCC                                37500
    PTDHDY=(MAGI(NX,KP)-MAGI(NX,KP-1))/K                                 37600
270 GIXP=GIXP+PTDHDY/PTNE*H                                              37700
                                                                         37800
    EVALUATION OF GRAPHICAL INTEGRAL ALONG THE Y AXIS                    37900
                                                                         38000
280 KPM1=KP-1                                                            38100
    GIY=0.0                                                              38200
    DO 290 NY=KN,KPM1                                                    38300
    PTNE=(NS(KX,NY)+NS(KX,NY+1))/2.0+ACCC                                38400
    PTDHDX=(MAGI(KX+1,NY)-MAGI(KX,NY))/H                                 38500
290 GIY=GIY+PTDHDX/PTNE*K                                                38600
                                                                         38700
    EVALUATION OF OUTPUT VOLTAGE, POWER AND EFFICIENCY                   38800
                                                                         38900
    OHMLOSS=KTOE/1.6E-19/(DN+DP)*(GIXN-GIY-GIXP)                         39000
    DIFFPOT=KTOE*(DN-DP)/(DN+DP)*ALOG((NP+ACCC)/(NN+ACCC))               39100
    JUNCPOT=KTOE*ALOG((NN+NO)*(NP+PO)/NI/NI)                             39200
    VOLTAGE=JUNCPOT+DIFFPOT-OHMLOSS                                      39300
    POWER=VOLTAGE*CURRENT                                                39400
    ETA=POWER/POWMAX                                                     39500
    ETACURD=CURRENT/CURMAX                                               39600
    ETAV=VOLTAGE/VGAP                                                    39700
                                                                         39800
```

```
      WRITEOUT OF VALJES RELATED TO CURDNET, VOLTAGE AND POWER                  3990
                                                                                4000
      IF(IPATH.EQ.1)  GO TO 300                                                 4005
      WRITE (6,550) CJRDNET,VOLTAGE,JUNCPOT,DIFFPOT,OHMLOSS                     4010
      WRITE (6,550) POWER,POWMAX,ETA,ETACURD,ETAV                               4020
                                                                                4030
      RESET OF PATH OF INTEGRATION                                              4040
                                                                                4050
  300 KN=KN-1                                                                   4060
      IF (PATHNMB.EQ.1) GO TO 310                                               4070
      KP=SP1+(JNM1-SP1)*(PATHKNT)/(PATHNMB-1)                                   4080
      KX=2+(INM1-2)*(PATHKNT)/(PATHNMB-1)                                       4090
  310 CONTINUE                                                                  4100
                                                                                4120
      START A NEW MESH UNLESS THE FINEST MESH HAS JUST BEEN COMPLETED           4130
                                                                                4140
      IF (MESHKNT.NE.MESHNMB) GO TO 450                                         4150
                                                                                4160
      BEGIN STORAGE AND INTERPOLATION WITH PROCEEDURE FOR FIRST ITERATION       4170
                                                                                4180
      IF (PTKNT.NE.1) GO TO 340                                                 4190
      DO 320 NX=1,IN                                                            4200
      DO 320 NY=1,JN                                                            4210
  320 NS2(NX,NY)=NS(NX,NY)                                                      4220
      DO 330 NX=2,IHM1                                                          4230
      DO 330 NY=2,JHM1                                                          4240
  330 MAGI2(NX,NY)=MAGI(NX,NY)                                                  4250
      V2=VOLTAGE                                                                4260
      VOLT(1)=V2                                                                4270
      C2=CJRDNET                                                                4280
      CRNT(1)=C2                                                                4290
      PTKNT=2                                                                   4300
                                                                                4302
      EVALUATION OF CURRENT AND VOLTAGE INCREMENTS                              4305
                                                                                4306
      CINCREG=CJRDMAX/NCINC                                                     4308
      CURDINC=CINCREG                                                           4309
      CURDNET=CJRDNET+CURDINC                                                   4310
      GO TO 10                                                                  4320
                                                                                4330
      INTERPOLATION PROCEEDURE FOR SECOND ITERATION                             4340
                                                                                4350
  340 IF (PTKNT.NE.2) GO TO 390                                                 4360
      DO 350 NX=1,IN                                                            4370
      DO 350 NY=1,JN                                                            4380
  350 NS1(NX,NY)=NS(NX,NY)                                                      4390
      DO 360 NX=2,IHM1                                                          4400
      DO 360 NY=2,JHM1                                                          4410
  360 MAGI1(NX,NY)=MAGI(NX,NY)                                                  4420
      V1=VOLTAGE                                                                4430
      VOLT(2)=V1                                                                4440
      C1=CJRDNET                                                                4450
      CRNT(2)=C1                                                                4460
      PTKNT=3                                                                   4470
      CURDNET=CJRDNET+CURDINC                                                   4480
      DO 370 NX=1,IN                                                            4490
      DO 370 NY=1,JN                                                            4500
  370 NS(NX,NY)=NS1(NX,NY)+NS(NX,NY)-NS2(NX,NY)                                 4510
      DO 380 NX=2,IHM1                                                          4520
      DO 380 NY=2,JHM1                                                          4530
  380 MAGI(NX,NY)=MAGI1(NX,NY)+MAGI1(NX,NY)-MAGI2(NX,NY)                        4540
```

```
      GO TO 440                                                          45500
                                                                         45600
      BEGIN QUADRATIC INTERPOLATIONS WITH INITIALIZATIONS                45700
                                                                         45800
  390 C3=C2                                                              45900
      C2=C1                                                              46000
      C1=CURDNET                                                         46100
      CRNT(PTKNT)=C1                                                     46200
      V3=V2                                                              46300
      V2=V1                                                              46400
      V1=VOLTAGE                                                         46500
      VOLT(PTKNT)=V1                                                     46600
                                                                         46700
      COMPUTATION OF MATRIX ELEMENTS                                     46800
                                                                         46900
      D11=-1.0/(C3-C1)/(C1-C2)                                           47000
      D12=-1.0/(C1-C2)/(C2-C3)                                           47100
      D13=-1.0/(C2-C3)/(C3-C1)                                           47200
      D21=(C2+C3)/(C3-C1)/(C1-C2)                                        47300
      D22=(C3+C1)/(C1-C2)/(C2-C3)                                        47400
      D23=(C1+C2)/(C2-C3)/(C3-C1)                                        47500
      D31=-C2*C3/(C3-C1)/(C1-C2)                                         47600
      D32=-C3*C1/(C1-C2)/(C2-C3)                                         47700
      D33=-C1*C2/(C2-C3)/(C3-C1)                                         47800
                                                                         47820
      EVALUATION OF VOLTAGE COEFFICIENTS                                 47840
                                                                         47860
      AV=D11*V1+D12*V2+D13*V3                                            47880
      BV=D21*V1+D22*V2+D23*V3                                            47901
      CV=D31*V1+D32*V2+D33*V3                                            47920
      IF((AMIN1(V1,V2,V3).LT.KTOE).AND.(INDXETA.EQ.4)) GO TO 520         47940
      IF((NN.LT.NI).OR.(NP.LT.NI)) GO TO 520                             47960
                                                                         47980
      REFINED ESTIMATE OF MAXIMUM POWER POINT                            48001
                                                                         48020
      IF(INDXETA.NE.3) GO TO 395                                         48040
    4 INDXETA=4                                                          48060
      CALL CRVFIT(CRNT,VOLT,PTKNT,INDXETA,CMAXPOW,PMAXPOW)               48080
      PMAXPOW=PMAXPOW/CMAXPOW                                            48100
                                                                         48120
      TEST FOR ETAMAX                                                    48200
                                                                         48300
    5 IF(INDXETA.EQ.2) GO TO 396                                         48400
      IF ((ETA.GT.ETA1).OR.(INDXETA.NE.1)) GO TO 397                     48500
    6 INDXETA=INDXETA+1                                                  48600
      CALL CRVFIT(CRNT,VOLT,PTKNT,INDXETA,CURDNET,PMAXPOW)               48700
      DIFMIN=AMIN1(ABS(C1-CURDNET),ABS(C2-CURDNET))                      48800
      RATIO=DIFMIN/CURDNET                                               48900
      IF(RATIO.LT.0.003) GO TO 394                                       49000
      IF(IITVAR.EQ.1) GO TO 410                                          49100
      WRITE (6,590)                                                      49200
      GO TO 410                                                          49300
                                                                         49400
      COMPUTATION OF CURDNET                                             49500
                                                                         49600
    7 CURDNET=AMAX1(C1,C2,C3)+CINCRG                                     49700
      JNM3=IN-3                                                          49800
      DO 399 NY=2,JNM1,JNM3                                              49900
      N1=NS(2,NY)+NS(1,NY)                                               50000
      N2=NS1(2,NY)+NS1(1,NY)                                             50100
      N3=NS2(2,NY)+NS2(1,NY)                                             50200
```

```
      F11=-1.0/(N3-N1)/(N1-N2)                                          4950
      F12=-1.0/(N1-N2)/(N2-N3)                                          4974
      F13=-1.0/(N2-N3)/(N3-N1)                                          4979
      F21=-(N2+N3)*F11                                                  4994
      F22=-(N3+N1)*F12                                                  4999
      F23=-(N1+N2)*F13                                                  4994
      F31=N2*N3*F11                                                     4999
      F32=N3*N1*F12                                                     5004
      F33=N1*N2*F13                                                     5009
      A=F11*C1+F12*C2+F13*C3                                            5014
      B=F21*C1+F22*C2+F23*C3                                            5019
      C=F31*C1+F32*C2+F33*C3                                            5024
      NSRF=AMIN1(N1,N2,N3)*RF                                           5029
      CURDTRY=A*NSRF*NSRF+B*NSRF+C                                      5034
399   CURDNET=AMIN1(CJRDNET,CURDTRY)                                    5037
C                                                                       5040
C     INTERPOLATION FOR NS                                              5050
C                                                                       5060
410   CURDNTS=CJRDNET*CURDNET                                           5075
      DO 420 NX=1,IN                                                    5090
      DO 420 NY=1,JN                                                    5100
      NS3(NX,NY)=NS2(NX,NY)                                             5110
      NS2(NX,NY)=NS1(NX,NY)                                             5120
      NS1(NX,NY)=NS(NX,NY)                                              5130
      A=D11*NS1(NX,NY)+D12*NS2(NX,NY)+D13*NS3(NX,NY)                    5140
      B=D21*NS1(NX,NY)+D22*NS2(NX,NY)+D23*NS3(NX,NY)                    5150
      C=D31*NS1(NX,NY)+D32*NS2(NX,NY)+D33*NS3(NX,NY)                    5160
420   NS(NX,NY)=A*CJRDNTS+B*CURDNET+C                                   5170
C                                                                       5180
C     INTERPOLATION FOR MAGI                                            5190
C                                                                       5200
      DO 430 NX=2,IHM1                                                  5210
      DO 430 NY=2,JHM1                                                  5220
      MAGI3(NX,NY)=MAGI2(NX,NY)                                         5230
      MAGI2(NX,NY)=MAGI1(NX,NY)                                         5240
      MAGI1(NX,NY)=MAGI(NX,NY)                                          5250
      A=D11*MAGI1(NX,NY)+D12*MAGI2(NX,NY)+D13*MAGI3(NX,NY)              5260
      B=D21*MAGI1(NX,NY)+D22*MAGI2(NX,NY)+D23*MAGI3(NX,NY)              5270
      C=D31*MAGI1(NX,NY)+D32*MAGI2(NX,NY)+D33*MAGI3(NX,NY)              5280
430   MAGI(NX,NY)=A*CJRDNTS+B*CURDNET+C                                 5290
      PTKNT=PTKNT+1                                                     5300
440   ETA1=ETA                                                          5310
      GO TO 40                                                          5320
C                                                                       5330
C     CHECK AND INCREMENT MESHKNT                                       5340
C                                                                       5350
450   MESHKNT=MESHKNT+1                                                 5360
C                                                                       5370
C     BEGIN REMESHING BY STORING NS IN DUMMY AND MAGI IN DUMAG          5380
C                                                                       5390
      IX=1                                                              5400
      DO 470 NX=1,IN                                                    5410
      IY=1                                                              5420
      DO 460 NY=1,JN                                                    5430
      DUMMY(IX,IY)=NS(NX,NY)                                            5440
      DUMAG(IX,IY)=MAGI(NX,NY)                                          5450
460   IY=IY+3                                                           5460
470   IX=IX+3                                                           5470
C                                                                       5480
C     COMPUTE DUMMY AND DUMAG AT HORIZONTAL INTERMEDIATE POINTS         5490
C                                                                       5500
```

```
      IXMAX=3*INM1+1                                                    55100
      ILEFTMX=3*JN-5                                                    55200
      DO 480 IX=1,IXMAX,3                                               55300
      DO 480 ILEFT=1,ILEFTMX,3                                          55400
      IRIGHT=ILEFT+3                                                    55500
      DUMMY(IX,ILEFT+1)=(DUMMY(IX,ILEFT)+DUMMY(IX,ILEFT)+DUMMY(IX,IRIGHT  55600
     1))/3.0                                                            55700
      DUMAG(IX,ILEFT+1)=(DUMAG(IX,ILEFT)+DUMAG(IX,ILEFT)+DUMAG(IX,IRIGHT  55800
     1))/3.0                                                            55900
      DUMMY(IX,ILEFT+2)=(DUMMY(IX,ILEFT)+DUMMY(IX,IRIGHT)+DUMMY(IX,IRIGH  56000
     1T))/3.0                                                           56100
      DUMAG(IX,ILEFT+2)=(DUMAG(IX,ILEFT)+DUMAG(IX,IRIGHT)+DUMAG(IX,IRIGH  56200
     1T))/3.0                                                           56300
                                                                        56400
      COMPUTE DUMMY AND DUMAG AT VERTICAL INTERMEDIATE POINTS           56500
                                                                        56600
      ILOWMAX=3*IN-5                                                    56700
      IYMAX=3*JNM1+1                                                    56800
      DO 490 ILOW=1,ILOWMAX,3                                           56900
      DO 490 IY=1,IYMAX                                                 57000
      IHIGH=ILOW+3                                                      57100
      DUMMY(ILOW+1,IY)=(DUMMY(ILOW,IY)+DUMMY(ILOW,IY)+DUMMY(IHIGH,IY))/3  57200
     1.0                                                                57300
      DUMMY(ILOW+2,IY)=(DUMMY(ILOW,IY)+DUMMY(IHIGH,IY)+DUMMY(IHIGH,IY))/  57400
     13.0                                                               57500
      DUMAG(ILOW+1,IY)=(DUMAG(ILOW,IY)+DUMAG(ILOW,IY)+DUMAG(IHIGH,IY))/3  57600
     1.0                                                                57700
      DUMAG(ILOW+2,IY)=(DUMAG(ILOW,IY)+DUMAG(IHIGH,IY)+DUMAG(IHIGH,IY))/  57800
     13.0                                                               57900
                                                                        58000
      TRANSFER DUMMY INTO NEW VS MESH                                   58100
                                                                        58200
      IN=3*IN-4                                                         58300
      JN=3*JN-4                                                         58400
      DO 500 NX=1,IN                                                    58500
      DO 500 NY=1,JN                                                    58600
      VS(NX,NY)=DUMMY(NX+1,NY+1)                                        58700
                                                                        58800
      TRANSFER DUMAG INTO NEW MAGI MESH                                 58900
                                                                        59000
      IM=3*IM-4                                                         59100
      DO 510 NX=1,IM                                                    59200
      DO 510 NY=1,JN                                                    59300
      MAGI(NX,NY)=DUMAG(NX+2,NY)                                        59400
                                                                        59500
      RESET I AND J TO THE NUMBER OF INCREMENTS IN THE NEW MESH         59600
                                                                        59700
      I=I+I+I                                                           59800
      J=J+J+J                                                           59900
                                                                        60000
      BEGIN NEW MESH                                                    60100
                                                                        60200
      GO TO 30                                                          60300
                                                                        60400
      SUMMARY WRITEOUT OF VOLTAGE, CURRENT AND EFFICIENCY               60500
                                                                        60600
      PRINT=PRINT-1                                                     60700
      WRITE (6,600)                                                     60800
      DO 520 INDX=1,PRINT                                               60900
      VOLTEMP=VOLT(INDX)                                                61000
      CURTEMP=CRNT(INDX)                                                61100
```

```
      ETA=CURDTMP*VOLTTMP/POWMAX                                        61400
      IF(ICURVE.EQ.1)  GO TO 530                                        61460
      WRITE (6,610) INDX,CURDTMP,VOLTTMP,ETA                            61540
  530 CONTINUE                                                          61600
C                                                                       61700
C     SUMMARY OF OUTPUT RESULTS                                         61800
C                                                                       61900
      VOC = VOLT(1)                                                     62000
      VF=VOC/VGAP                                                       62100
      CURDSC=(-BV-SQRT(BV*BV-4.0*AV*CV))/2.0/AV                         62200
      ETACOL=CURDSC/CURDMAX                                             62300
      CF=PMAXPOW/VOC/CURDSC                                             62400
      ETACELL=PMAXPOW/POWMAX                                            62500
      WRITE(6,620) VOC,VF,CURDSC,ETACOL,PMAXPOW,CMAXPOW,VMAXPOW,CF,     62600
     1ETACELL,XO,LN,LP,LI,ENR                                           62700
  620 FORMAT(/,1X,5HVOC = ,F6.4,/,1X,5HVF = ,F6.4,/,1X,9HCURDSC = ,     62800
     1E10.3,/,1X,9HETACOL = ,F6.4,/,1X,10HPMAXPOW = ,E10.3,/,           62900
     21X,10HCMAXPOW = ,E10.3,/,1X,10HVMAXPOW = ,F6.4,/,1X,5HCF = ,      63000
     3F6.4,/,1X,10HETACELL = ,F6.4,/,1X,5HXO = ,E10.3,/,1X,5HLN = ,E10.3 63100
     4,/,1X,5HLP = ,E10.3,/,1X,5HLI = ,E10.3,/,1X,6HENR = ,E10.3)       63200
C                                                                       63300
C     STORE OUTPUTS IN VECTORS                                          63400
C                                                                       63500
      VOCD(ID)=VOC                                                      63600
      VFD(ID)=VF                                                        63700
      CURDSCD(ID)=CURDSC                                                63800
      CURDMXD(ID)=CURDMAX                                               63900
      ETACOLD(ID)=ETACOL                                                64000
      PMXPOWD(ID)=PMAXPOW                                               64100
      CMXPOWD(ID)=CMAXPOW                                               64200
      VMXPOWD(ID)=VMAXPOW                                               64300
      CFD(ID)=CF                                                        64400
      ETAD(ID)=ETACELL                                                  64500
      XNLN(ID)=NLN                                                      64600
      XNLP(ID)=NLP                                                      64700
      XXO(ID)=NXO                                                       64800
      IF(ISPTS.EQ.1)  GO TO 730                                         64900
C                                                                       65000
C     SELECT NEW MESH PARAMETERS                                        65100
C                                                                       65200
      IF(IC.EQ.1)  NLNI=NLNT-1                                          65300
      IF(IC.EQ.2)  NLNI=NLNT+1                                          65400
      IF(IC.EQ.3)  NLPI=NLPT-1                                          65500
      IF(IC.EQ.4)  NLPI=NLPT+1                                          65600
      IF(IC.EQ.5)  NXOI=NXOT-1                                          65700
      IF(IC.EQ.6)  NXOI=NXOT+1                                          65800
C                                                                       65900
C     HAVE OUTPUTS BEEN EVALUATED FOR NEW MESH PARAMETERS               66000
C                                                                       66100
      IEL=IEVAL(NLNI,NLPI,NXOI)                                         66200
      IF(IEL.EQ.0)  GO TO 5                                             66300
C                                                                       66400
C     IS POWER OUTPUT FOR NEAREST MESH GREATER THAN MAXIMUM POWER       66500
C     OUTPUT FROM PREVIOUS MESHES                                       66600
C                                                                       66700
      IF(NLNI.EQ.NLNT.AND.NLPI.EQ.NLPT.AND.NXOI.EQ.NXOT) GO TO 720      66800
      IF(NXOI.EQ.NXOT.AND.NLPI.EQ.NLPT) GO TO 720                       66900
      IF(NLNI.EQ.NLNT.AND.NXOI.EQ.NXOT) GO TO 720                       67000
      NLNT=NLNI                                                         67100
      NLPT=NLPI                                                         67200
```

```
      NXOT=NXO1                                                          6[illegible]
      IDXXOM=3                                                           6[illegible]
      IT=IC                                                              67300
      I3PTS=0                                                            67400
      GO TO 700                                                          67500
C                                                                        67600
C     HAS THE POWER OUTPUT BEEN EVALUATED FOR THE SIX MESH               67700
C     ARRANGEMENTS ADJASCENT TO THE MESH MAXIMUM POWER POINT             67800
C                                                                        67900
720   IC=IC+1                                                            68000
      IF(IC.EQ.7)  IC=1                                                  68100
      NLN1=NLNT                                                          68200
      NLP1=NLPT                                                          68300
      NXO1=NXOT                                                          68400
      IF(IC.NE.IT)  GO TO 700                                            68500
C                                                                        68600
C     EVALUATION OF OUTPUT PARAMETERS FOR 3 ADDITIONAL POINTS            68700
C                                                                        68800
      I3PTS=1                                                            68900
      JLNP=IEVAL(NLNT+1,NLPT,NXOT)                                       69000
      JLNM=IEVAL(NLNT-1,NLPT,NXOT)                                       69100
      JLPP=IEVAL(NLNT,NLPT+1,NXOT)                                       69200
      JLPM=IEVAL(NLNT,NLPT-1,NXOT)                                       69300
      JXOP=IEVAL(NLNT,NLPT,NXOT+1)                                       69400
      JXOM =IEVAL(NLNT,NLPT,NXOT-1)                                      69500
      ICLN=-1                                                            69600
      IF(PMXPOWD(JLNP).GT.PMXPOWD(JLNM))  ICLN=1                         69700
      RICLN=ICLN                                                         69800
      ICLP=-1                                                            69900
      IF(PMXPOWD(JLPP).GT.PMXPOWD(JLPM))  ICLP=1                         70000
      RICLP=ICLP                                                         70100
      ICXO=-1                                                            70200
      IF(PMXPOWD(JXOP).GT.PMXPOWD(JXOM))  ICXO=1                         70300
      RICXO=ICXO                                                         70400
730   LNLP=IEVAL(NLNT+ICLN,NLPT+ICLP,NXOT)                               70500
      LNXO=IEVAL(NLNT+ICLN,NLPT,NXOT+ICXO)                               70600
      LPXO=IEVAL(NLNT,NLPT+ICLP,NXOT+ICXO)                               70700
      NLN1=NLNT+ICLN                                                     70800
      NLP1=NLPT+ICLP                                                     70900
      NXO1=NXOT                                                          71000
      IF(LNLP.EQ.0)  GO TO 5                                             71100
      IF(PMXPOWD(IET).LT.PMXPOWD(LNLP))  GO TO 710                       71200
      NLP1=NLPT                                                          71300
      NXO1=NXOT+ICXO                                                     71400
      IF(NXO1.EQ.NXOMIN)  GO TO 732                                      71500
      IF(LNXO.EQ.0)  GO TO 5                                             71600
      IF(PMXPOWD(IET).LT.PMXPOWD(LNXO))  GO TO 710                       71700
      NLN1=NLNT                                                          71800
      NLP1=NLPT+ICLP                                                     71900
      IF(LPXO.EQ.0)  GO TO 5                                             72000
      IF(PMXPOWD(IET).LT.PMXPOWD(LPXO)) GO TO 710                        72100
C                                                                        72200
C     EVALUATION OF COEFFICIENTS FOR POWER IN SECOND ORDER EXPANSION     72300
C                                                                        72400
      CALL COEFF(PMXPOWD)                                                [illegible]
C                                                                        [illegible]
C     USE OF LIBRARY SUBROUTINE TO FIND INTERPOLATED MAXIMUM             [illegible]
C     POWER POINT                                                        [illegible]
C                                                                        [illegible]
750   CALL SYMPOL(AM,BM,XM,3,IDXXM,1,ISE)                                [illegible]
      IF(ISE.NE.0)  GO TO 750                                            [illegible]
```

```
      IF(IDXXOM.EQ.2)  XM(3,1)=0                                          7295.
      D  735  NX=1,3                                                      7300.
735   XM(NX,1)=-0.5*XM(NX,1)                                              7310.
C                                                                         7320.
C     EVALUATION OF OUTPUTS AT INTERPOLATED MAXIMUM POWER POINT           7330.
C                                                                         7340.
      PMAXPOW=D(PMXPOWD(IET),BM,AM,XM)                                    7350.
      NLN=NLNT                                                            7360.
      NLP=NLPT                                                            7370.
      NXO=NXOT                                                            7380.
      NLN=NLN+XM(1,1)                                                     7390.
      NLP=NLP+XM(2,1)                                                     7400.
      NXO=NXO+XM(3,1)                                                     7410.
      WRITE(6,660) NLN,NLP,NXO,AM,BM                                      7420.
660   FORMAT(3E13.3)                                                      7430.
      IF(AM(1,2).EQ.0.) GO TO 737                                         7440.
      CALL  EIGEN(AM,EIGVAL,3,IDXXOM,1)                                   7450.
      WRITE(6,560)                                                        7460.
      WRITE(6,660) EIGVAL,AM                                              7470.
737   CALL COEFF(CMXPOWD)                                                 7480.
      CMAXPOW =D(CMXPOWD(IET),BM,AM,XM)                                   7490.
      CALL COEFF(VOCD)                                                    7500.
      VOC=D(VOCD(IET),BM,AM,XM)                                           7510.
      CALL COEFF(CJRDSCD)                                                 7520.
      CJRDSC=D(CJRDSCD(IET),BM,AM,XM)                                     7530.
      CALL COEFF(CJRDMXD)                                                 7540.
      CJRDMAX=D(CJRDMXD(IET),BM,AM,XM)                                    7550.
      VGAP=VOC/VGAP                                                       7560.
      CJRCOL=CJRDSC/CJRDMAX                                               7570.
      PMAXPOW=PMAXPOW/CMAXPOW                                             7580.
      VF=CMAXPOW/VOC/CJRDSC                                               7590.
      CFILL=VF*CF*ETACOL                                                  7600.
      VGAP=VGAP*CJRDMAX                                                   7610.
      NLN=NLN*K(2,3                                                       7620.
      NLP=NLP*K(2,3                                                       7630.
      NXO=NXO*K                                                           7640.
C                                                                         7650.
C     WRITE OUTPUTS                                                       7660.
C                                                                         7670.
      WRITE(6,625) N,K,LI,CURDOPT,ISE                                     7680.
625   FORMAT(/,/,1X,4HN  = ,E9.3,2X,4HK  = ,E9.3,2X,5HLI  = ,E9.3,2X,     7690.
     1 6HCURDOPT = ,E9.3,2X,6HISE = ,I1,/,/)                              7700.
      WRITE(6,630)                                                        7710.
630   FORMAT(1X,3HID ,3HLN ,3HLP ,3HXO ,6HVOC    ,6HVF     ,10HCURDSC    ,7720.
     1 6HETAC  ,10HCURDMAX   ,10HCMAXPOW   ,6HVMXPW ,10HPMAXPOW   ,       7730.
     2 6HCF    ,5HETACL,/)                                               7740.
      DO 740  IP=1,ID                                                     7750.
40    WRITE(6,640) IP,JNLN(IP),JNLP(IP),JNXO(IP),VOCD(IP),VFD(IP),       7760.
     1 JCDSCD(IP),ETACOLD(IP),CJRDMXD(IP),CMXPOWD(IP),VMXPOWD(IP),        7770.
     2 PMXPOWD(IP),FFD(IP),ETAD(IP)                                       7780.
640   FORMAT(4I3,2F6.4,F10.3,F6.4,2E10.3,F6.4,E10.3,2F6.4)               7790.
      WRITE(6,650)  LN,LP,XO,VOC,VF,CURDSC,ETACOL,CURDMAX,CMAXPOW,        7800.
     1 VMXPOW,PMAXPOW,PDPMAX,CF,ETAFILL                                   7810.
650   FORMAT(/,/,5H LN  =,E10.3,/,5H LP  =,E10.3,/,5H XO  =,E10.3,/,      7820.
     1 5H VOC =,E10.3,/,5H VF  =,F6.4,/,9H CURDSC =,E10.3,/,9H ETACOL =,  7830.
     2 F6.4,/,10H CURDMAX =,E10.3,/,10H CMAXPOW =,E10.3,/,10H VMAXPOW =,  7840.
     3 E10.3,/,10H PMAXPOW =,E10.3,/,10H PDPMAX =,E10.3,/,5H CF  =,F6.4,/,7850.
     4 10H ETAFILL =,F6.4)                                                7860.
      END                                                                 7870.
```

```
      ...,2,1)=AM(2,1)=0                                                    78630
      AM(3,1)=AM(1,3)=0                                                     78640
      AM(2,3)=AM(3,2)=0                                                     78650
      GO TO 733                                                             78660
                                                                            78700
  1   FORMAT (1X,17HSUCCESSFULL EXIT ,/)                                    78800
  2     ORMAT (1X,5(2X,E13.6))                                              78900
  3   FORMAT (1X)                                                           79000
  4   FORMAT (1X,9HMESHKNT =,I4,9HLOOPKNT =,I4,/)                           79100
  5   FORMAT (/,/,1X,9HMESHKNT =,I2,1X,9HPATHKNT =,I2,/)                    79200
  6   FORMAT (/,/,1X,27H MAXIMUM EFFICIENCY VALUES ,/,/)                    79300
  7     ORMAT (/,/,1X,5HPTKNT,6X,7HCURRENT,8X,7HVOLTAGE,8X,3HETA,/)         79400
  8   FORMAT (1X,I5,4(5X,E10.3))                                            79500
      FORMAT(12X,E12.4)                                                     79550
      END                                                                   79600
```

```
      SUBROUTINE  COEFF(DM)                                              79700
      COMMON  IET,JLNP,JLNM,JLPP,JLPM,JXOP,JXOM,LNLP,LNXO,LPXO,RICLN,    79800
     1 RICLP,RICXO,BM(3,3),AM(3,3),JNLN(50),JNLP(50),JNXO(50),ID         79900
      DIMENSION  DM(50)                                                  80000
      AM(1,1)=(DM(JLNP)+DM(JLNM))/2.0-DM(IET)                            80100
      BM(1,1)=(DM(JLNP)-DM(JLNM))/2.0                                    80200
      AM(2,2)=(DM(JLPP)+DM(JLPM))/2.0-DM(IET)                            80300
      AM(2,1)=(DM(JLPP)-DM(JLPM))/2.0                                    80400
      AM(3,3)=(DM(JXOP)+DM(JXOM))/2.0-DM(IET)                            80500
      BM(3,1)=(DM(JXOP)-DM(JXOM))/2.0                                    80600
      AM(1,2)=AM(2,1)=(DM(LNLP)-DM(IET)-BM(1,1)*RICLN-BM(2,1)*RICLP      80700
     1-AM(1,1)-AM(2,2))/2.0/RICLN/RICLP                                  80800
      AM(1,3)=AM(3,1)=0.                                                 80900
      AM(2,3)=AM(3,2)=0.                                                 81000
      IF((LNXO.EQ.0).OR.(LPXO.EQ.0)) RETURN                              81100
      AM(1,3)=AM(3,1)=(DM(LNXO)-DM(IET)-BM(1,1)*RICLN-BM(3,1)*RICXO      81200
     1-AM(1,1)-AM(3,3))/2.0/RICLN/RICXO                                  81300
      AM(2,3)=AM(3,2)=(DM(LPXO)-DM(IET)-BM(2,1)*RICLP-BM(3,1)*RICXO      81400
     1-AM(2,2)-AM(3,3))/2.0/RICLP/RICXO                                  81500
      RETURN                                                             81600
      END                                                                81700
```

```
      FUNCTION  D(DIET,BM,AM,XM)                                        81500
      DIMENSION  AM(3,3),BM(3,1),XM(3,1)                                81600
      D=DIET                                                            81700
      DO 800  I=1,3                                                     81800
      D=D+BM(I,1)*XM(I,1)                                               81900
      DO 800  J=1,3                                                     81000
800   D=D+AM(I,J)*XM(I,1)*XM(J,1)                                       82000
      RETURN                                                            82100
      END                                                               82200
                                                                        82300
```

```
      FUNCTION IEVAL(NLN1,NLP1,NXO1)                                    8240
      COMMON  IET,JLNP,JLNM,JLPP,JLPM,JXOP,JXOM,LNLP,LNXO,LPXO,RICLN,   8250
     1RICLP,RICXO,BM(3,1),AM(3,3),JNLN(50),JNLP(50),JNXO(50),ID         8260
      IP=0                                                              8270
      IEVAL=0                                                           8280
810   IF(IP.EQ.ID) RETURN                                               8290
      IP=IP+1                                                           8300
      IF(NLN1.NE.JNLN(IP)) GO TO 810                                    8310
      IF(NLP1.NE.JNLP(IP))  GO TO 810                                   8320
      IF(NXO1.NE.JNXO(IP))  GO TO 810                                   8330
      IEVAL=IP                                                          8340
      RETURN                                                            8350
      END                                                               8360
```

```
      SUBROUTINE CRVFIT(CRNT,VOLT,PTKNT,INDXETA,CURONET,PMAXPOW)
      POWER PTKNT
      DIMENSION VOLT(30),CRNT(30),CM(30,30),T(30),TIM1(30),POWER(30)
     .  ,S(30)

C     TO POWER IN TERMS OF CURRENT AND VOLTAGE

      DO 1  I=1, PTKNT
      POWER(I)=VOLT(I)*CRNT(I)

C FIND POLYNOMIAL EXPRESSION FOR POWER IN TERMS OF SKEWED CURRENTS

      KNT=AMAX1(CRNT(PTKNT),CRNT(PTKNT-1),CRNT(PTKNT-2))
      T=AMAX1(POWER(PTKNT),POWER(PTKNT-1))
      DO 2 I=1,PTKNT
      CM(I,1)=1
      CRNS(I)=CRNT(I)-SKEW*POWER(I)
      DO   J=2,PTKNT
      M(I,J)=CM(I,J-1)*CRNS(I)
      CALL LINEQ1(CM,POWER,T,30,PTKNT,1,ILE)
      WRITE(6,3) ILE
      FORMAT(5HILE = ,I1)

C FIND THE MAXIMUM POWER POINT

      DO 4 I=2,PTKNT
      TIM1 I-1
      TIM1(I)=T(I)*RIM
      CRNS1=CRNS(PTKNT)
      PMAX=CPMAX(PTKNT-1)
      DO 5 I=1,3
      PP1=POLYAB(PTKNT,TIM1,CRNT1)
      PP2=POLY(PTKNT,TIM1,CRNT2)
      IF(PP1.EQ.PP2) GO TO 6
      CURONET=(PP1*(CRNT2-PP2*CRNT1)/(PP1-PP2)
      PMAXT=CPMAX
      CRNT1=CURONET
      GO TO 5

C COMPUTATION OF MAXIMUM POWER

      PMAX=POWER(1)
      JM1=1
      DO 7 J=1,PTKNT
      PMAXPOW=PMAX+T(J)*S(J)
      IF(PMAX.GT.PMAXPOW) GO TO 7

C SKEW CURRENT AT MAXIMUM POWER POINT

      CURONET=CURONET+SKEW*PMAX
      RETURN
      END
```

```
      SUBROUTINE TIMLE(PTKNT,TIME,CORONET)                              8875
      INTEGER PTKNT                                                     8880
      DIMENSION TIME(30)                                                8910
      PP=1                                                              8920
      TIME=0.                                                           8930
      DO 1 I=P,PTKNT                                                    8940
      TIME=PPRIME*TIME(I)+CIM2                                          8950
    1 TIME=CIM2*CORONET                                                 8960
      RETURN                                                            8970
      END                                                               8980
```

	1.0644E1	
	0.3113E19	
	3.4637E19	
[illegible]00E-03	3.7779E+19	2.6068E+21
[illegible]000E-03	4.0326E+19	1.6745E+21
[illegible]500E-03	4.2154E+19	1.2834E+21
[illegible]000E-03	4.3592E+19	1.0335E+21
[illegible]500E-03	4.4772E+19	8.6096E+20
[illegible]00E-03	4.5764E+19	7.3683E+20
[illegible]500E-03	4.6625E+19	6.4419E+20
[illegible]000E-02	4.7384E+19	5.7268E+20
1.1250E-02	4.8053E+19	5.1579E+20
1.2500E-02	4.8678E+19	4.6935E+20
1.3750E-02	4.9239E+19	4.3059E+20
1.5000E-02	4.9756E+19	3.9764E+20
1.6250E-02	5.0236E+19	3.6921E+20
1.7500E-02	5.0681E+19	3.4439E+20
1.8750E-02	5.1097E+19	3.2247E+20
2.0000E-02	5.1488E+19	3.0296E+20
2.1250E-02	5.1856E+19	2.8547E+20
2.2500E-02	5.2202E+19	2.6970E+20
2.3750E-02	5.2531E+19	2.5540E+20
2.5000E-02	5.2842E+19	2.4237E+20
2.6250E-02	5.3137E+19	2.3046E+20
2.7500E-02	5.3418E+19	2.1952E+20
[illegible]7 0E-02	5.3686E+19	2.0945E+20
[illegible]000E-02	5.3942E+19	2.0016E+20
[illegible]250E-02	5.4187E+19	1.9159E+20
[illegible]500E-02	5.4421E+19	1.8356E+20
[illegible]750E-02	5.4646E+19	1.7613E+20
[illegible]000E-02	5.4862E+19	1.6919E+20
[illegible]250E-02	5.5069E+19	1.6272E+20
[illegible]500E-02	5.5269E+19	1.5666E+20
[illegible]750E-02	5.5461E+19	1.5097E+20
[illegible]000E-02	5.5646E+19	1.4564E+20
[illegible]250E-02	5.5825E+19	1.4061E+20
[illegible]500E-02	5.5998E+19	1.3588E+20
[illegible]750E-02	5.6165E+19	1.3142E+20
[illegible]000E-02	5.6327E+19	1.2720E+20
[illegible]250E-02	5.6483E+19	1.2321E+20
[illegible]500E-02	5.6635E+19	1.1943E+20
[illegible]750E-02	5.6782E+19	1.1585E+20
[illegible]000E-02	5.6924E+19	1.1244E+20
[illegible]250E-02	5.7063E+19	1.0921E+20
5.2500E-02	5.7197E+19	1.0613E+20
5.3750E-02	5.7328E+19	1.0320E+20
5.5000E-02	5.7455E+19	1.0040E+20
[illegible]50E-02	5.7579E+19	9.7730E+19
[illegible]500E-02	5.7700E+19	9.5182E+19
[illegible]750E-02	5.7817E+19	9.2745E+19
5.8000E-02	5.7932E+19	9.0413E+19
5.8250E-02	5.8043E+19	8.8180E+19
[illegible]00E-02	5.8152E+19	8.6040E+19
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

7.2500E-02	5.8937E+19	7.1693E+19
7.3750E-02	5.9026E+19	7.0188E+19
7.5000E-02	5.9113E+19	6.8735E+19
7.6250E-02	5.9198E+19	6.7334E+19
7.7500E-02	5.9281E+19	6.5980E+19
7.8750E-02	5.9363E+19	6.4673E+19
8.0000E-02	5.9443E+19	6.3408E+19
8.1250E-02	5.9521E+19	6.2186E+19
8.2500E-02	5.9598E+19	6.1003E+19
8.3750E-02	5.9674E+19	5.9858E+19
8.5000E-02	5.9748E+19	5.8749E+19
8.6250E-02	5.9821E+19	5.7675E+19
8.7500E-02	5.9892E+19	5.6633E+19
8.8750E-02	5.9962E+19	5.5623E+19
9.0000E-02	6.0031E+19	5.4644E+19
9.1250E-02	6.0099E+19	5.3693E+19
9.2500E-02	6.0165E+19	5.2770E+19
9.3750E-02	6.0231E+19	5.1874E+19
9.5000E-02	6.0295E+19	5.1004E+19
9.6250E-02	6.0358E+19	5.0157E+19
9.7500E-02	6.0420E+19	4.9335E+19
9.8750E-02	6.0482E+19	4.8535E+19
1.0000E-01	6.0542E+19	4.7757E+19

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